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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 67-FM-43

April 14, 1967

TRAJECTORY DATA FOR HIGH-SPEED REENTRIES

By Walter Scott, Jr.
Guidance and Performance Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

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PROJECT APOLLO

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FIGURES

TRAJECTORY DATA FOR HIGH-SPEED REENTRIES

By Walter Scott, Jr.

SUMMARY AND INTRODUCTION

Typical maneuver envelopes, reentry groundtracks, altitude-range profiles, and communications blackout regions are plotted for open-loop (i.e., unguided) trajectories for lunar missions and for the guided entry trajectory of the AS-504 mission. The maneuver envelopes are open-ended, which means that skipout will occur at some bank angle, and the spacecraft will make one or more orbits around the earth. The maneuver envelopes were terminated at 3500 n. mi. down range, which represents the maximum distance that can be used without violating some other reentry condition. The maneuver envelopes represent the maximum cross-range maneuver capability of a spacecraft reentering at transearth velocities.

DISCUSSION OF DATA

All of the plots presented in this report were generated using middle-of-the-corridor parameters. Plots are presented for the general case, that is, for any lunar mission utilizing open-loop reentry trajectories, and for the AS-504 guided reentry trajectory.

Open-Loop Reentry Trajectories

Initial conditions at reentry for the general study were

Inertial velocity, fps	36 333
Inertial flight-path angle, deg	-6.1
Altitude, ft	400 000
Inclination, deg	30

The reentry maneuver envelopes were determined by holding the lift vector at a series of constant roll attitudes from 180° through 90° to a value that results in reentry ranges greater than 3500 n. mi., which represents the maximum operational maneuver capabilities of the spacecraft. The maneuver envelopes are shown in figures 1(a) through 1(d) for a standard atmosphere and lift-to-drag ratios (L/D) of 0.30, 0.35, 0.40, 0.45, respectively. The lunar-mission ground rules call for a nominal reentry maneuver capability of not less than 1000 n. mi. Therefore, the maneuver envelopes are defined such that reentry ranges of 1500 to 2500 n. mi. are attainable. However, under emergency conditions, such as a guidance and navigation (G&N) system failure, this ranging capability can be extended to 2000 n. mi. which increases the reentry range to 3500 n. mi.

Figures 2(a) through 2(d) show the reentry groundtracks for the same values of L/D as in figure 1. The point of entry for these groundtracks corresponds to 0-n. mi. down-range and cross-range distances.

Figures 3(a) through 3(d) present the peak load factor as a function of bank angle. From a crew safety standpoint, a bank angle of more than 90° would be intolerable.

Figures 4(a) through 4(d) present the altitude-range profiles for each bank angle. Time marks at 50-second intervals are indicated in order to show relative positions as a function of bank angle for the various reentry trajectories.

Figures 5(a) through 5(d) show altitude versus time from reentry. For a nominal reentry range of 1500 to 2000 n. mi., a typical reentry trajectory will require from 16 to 20 minutes from reentry interface to drogue parachute deployment.

Figures 6(a) through 6(d) present curves of altitude versus relative velocity and indicate communication blackout regions. Of particular interest are the entry and exit points in the various blackout regions. On some of the entry trajectories for which the down-range distance is greater the spacecraft exits from the blackout region. Since the peak altitude for the 3500-n. mi. down-range entry trajectories is nearly the same for all values of L/D, it becomes apparent that the skipout ranges are also about the same (approximately 1650 to 1700 n. mi.). This would imply that, with the same entry conditions, the skipout ranges from blackout are independent of L/D; rather the skipout range is dependent on down-range distance and peak altitude attained. The data for determining the blackout regions were obtained from reference 1.

AS-504 Guided Reentry Trajectories

Figures 7(a) through 7(f) and figure 8 are a series of curves which were generated using the AS-504 reentry state vector. The initial conditions at reentry were

Inertial velocity, fps	36 069
Inertial flight-path angle, deg	-6.26
Inclination, deg	37.9
Entry latitude, deg	9.4 S
Entry longitude, deg	156.8 E

With the exception of the guided run, figure 8, the data for the plots were computed in the same manner as for the general study, using a constant L/D of 0.388 and a ballistic coefficient of 72.61 lb/ft^2 for an 11 000-lb CM. Figure 7(e) is a plot of the maneuver envelope and groundtrack and figure 7(f) is the same plot on a map showing position with respect to land masses. When reentry occurs along the equator, the resulting maneuver envelope will be symmetrical. However, a shift in latitude of 9° at 38° inclination in the AS-504 trajectory results in what appears to be a nonsymmetrical maneuver envelope, which is caused by the changing coordinate system, the nonlinear latitude scale and Coriolis effects.

Figure 8 presents the reentry trajectory computed from a four-degree-of-freedom simulation program. Three degrees of freedom define the translational motion of the spacecraft center-of-mass, and the fourth degree of freedom defines the spacecraft roll attitude. The Massachusetts Institute of Technology reentry guidance program, MITREP VI (ref. 2), was used to control the guided reentry trajectory. The target point for this trajectory was 2000 n. mi. down range from reentry and is on a center line through the maneuver envelope. The trajectory shown in figure 8 was computed with the aerodynamic data with Mach number as shown below.

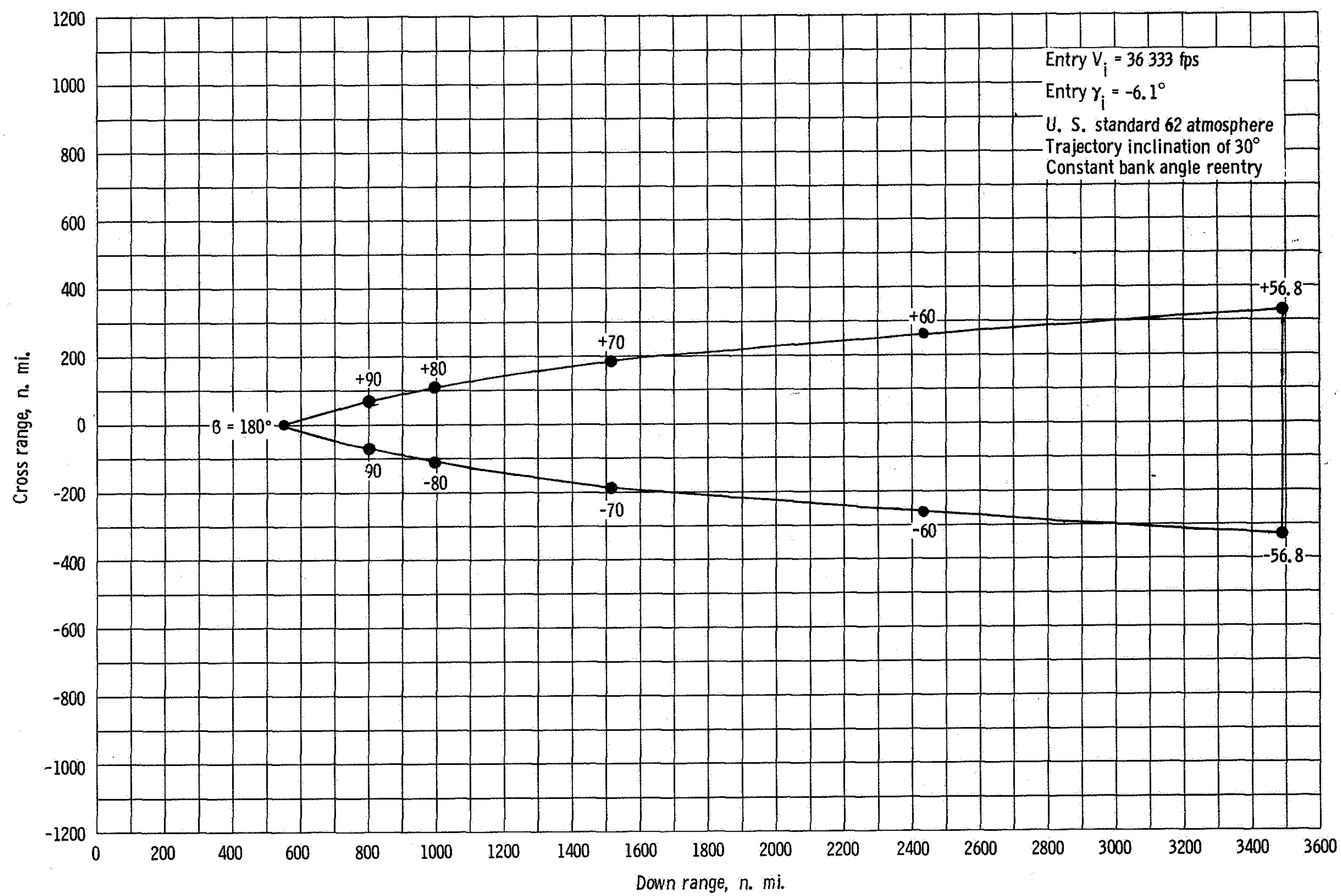
Figure 9 is actually a composite of all the plots of the general study. This figure shows by comparison the cross-range maneuver capabilities as a function of L/D for given down-range distances. As the L/D increases, the cross-range maneuver capability increases. This is also true for increases in down-range distances.

CONCLUDING REMARKS

For the longer reentry ranges for each set of reentry trajectories a peak altitude of about 380 000 ft is attained. In this trajectory there is a period of about 7 minutes in which the spacecraft is outside of the blackout region. The spacecraft exits blackout zone at about 290 000 ft, attains a peak altitude of about 380 000 ft, and again reenters the blackout zone at about 290 000 ft.

It is equally significant to know that the cross-range maneuver capability of the spacecraft increases as the L/D increases. For a nominal 2000 n. mi. down-range distance and for an L/D from 0.30 to 0.45, the cross-range maneuver capability increases from approximately 220 n. mi. to about 360 n. mi. These distances are, of course, increased as the down-range distance increases.

Peak altitude points are essentially the same for unguided entries as they are for guided entries; this is understandable since the spacecraft is traveling approximately the same distance down range. The spacecraft flying an open-loop trajectory maintains a fixed roll attitude, which induces the maximum cross-range displacement. In the guided entry the roll attitude is a function of time, velocity, altitude, down-range and cross-range distances, and range-to-target which minimizes the cross-range error without affecting the down-range distance. This assumes that in both cases splashdown is the same distance down range.



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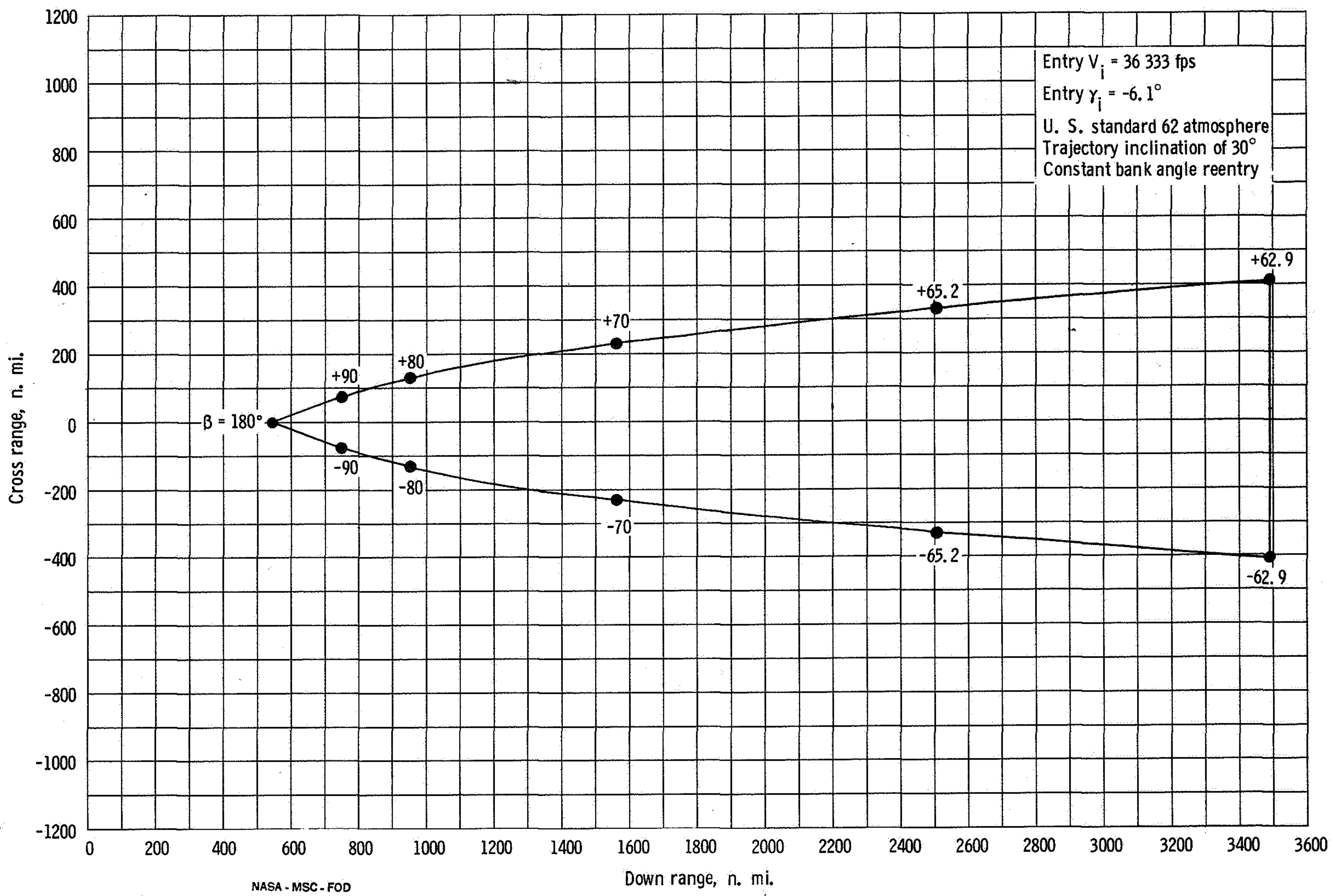
Plot No. 15,726 (a)
Date 6/21/66 W. Scott

(a) $L/D = 0.30,\ W/C_DA = 69.899.$

Figure 1. - Reentry maneuver envelope.



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Plot No. 15,727 (a)
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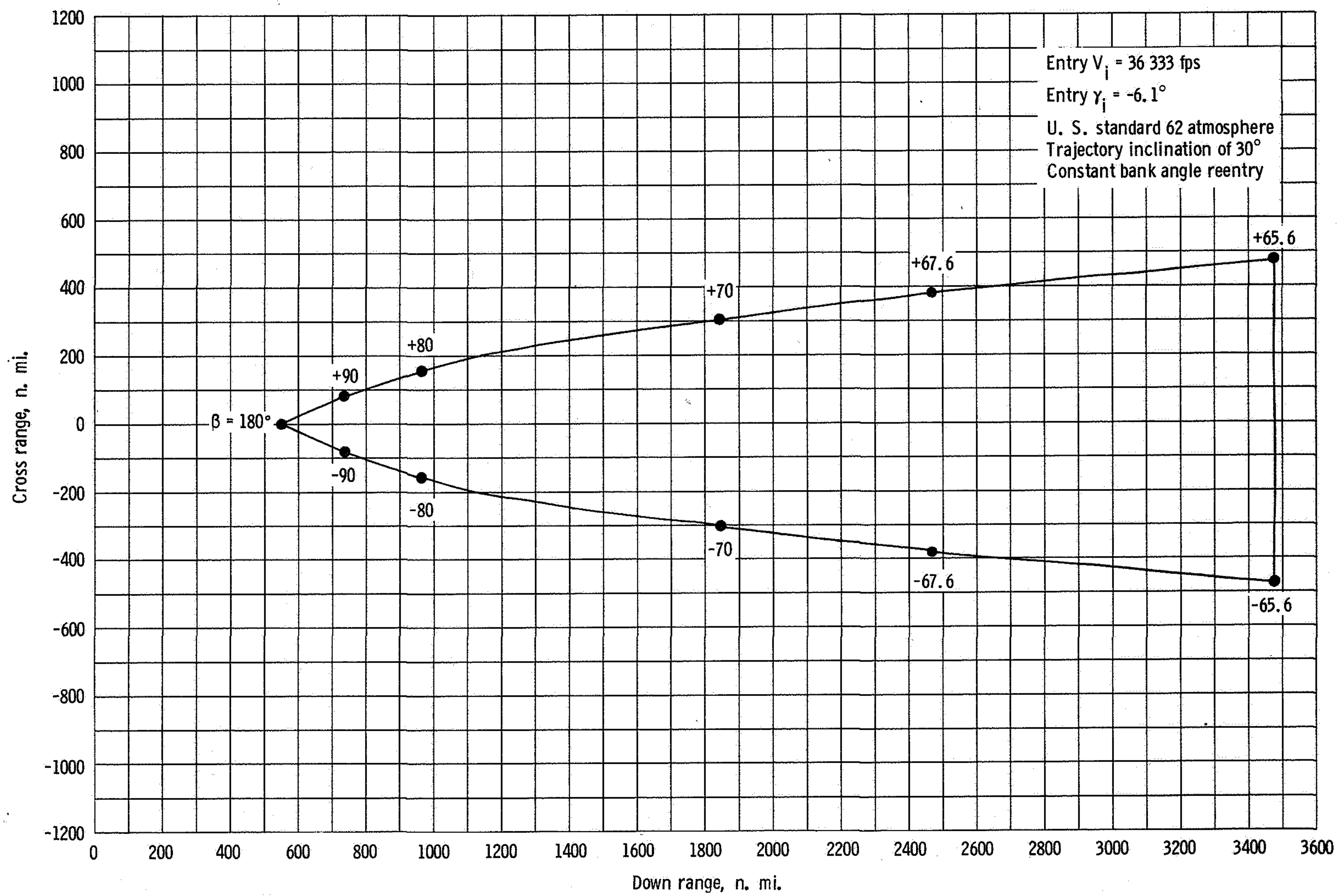
(b) L/D = 0.35, W/C_DA = 69.627.

Figure 1. - Continued.



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Plot No. 15,726 (a)
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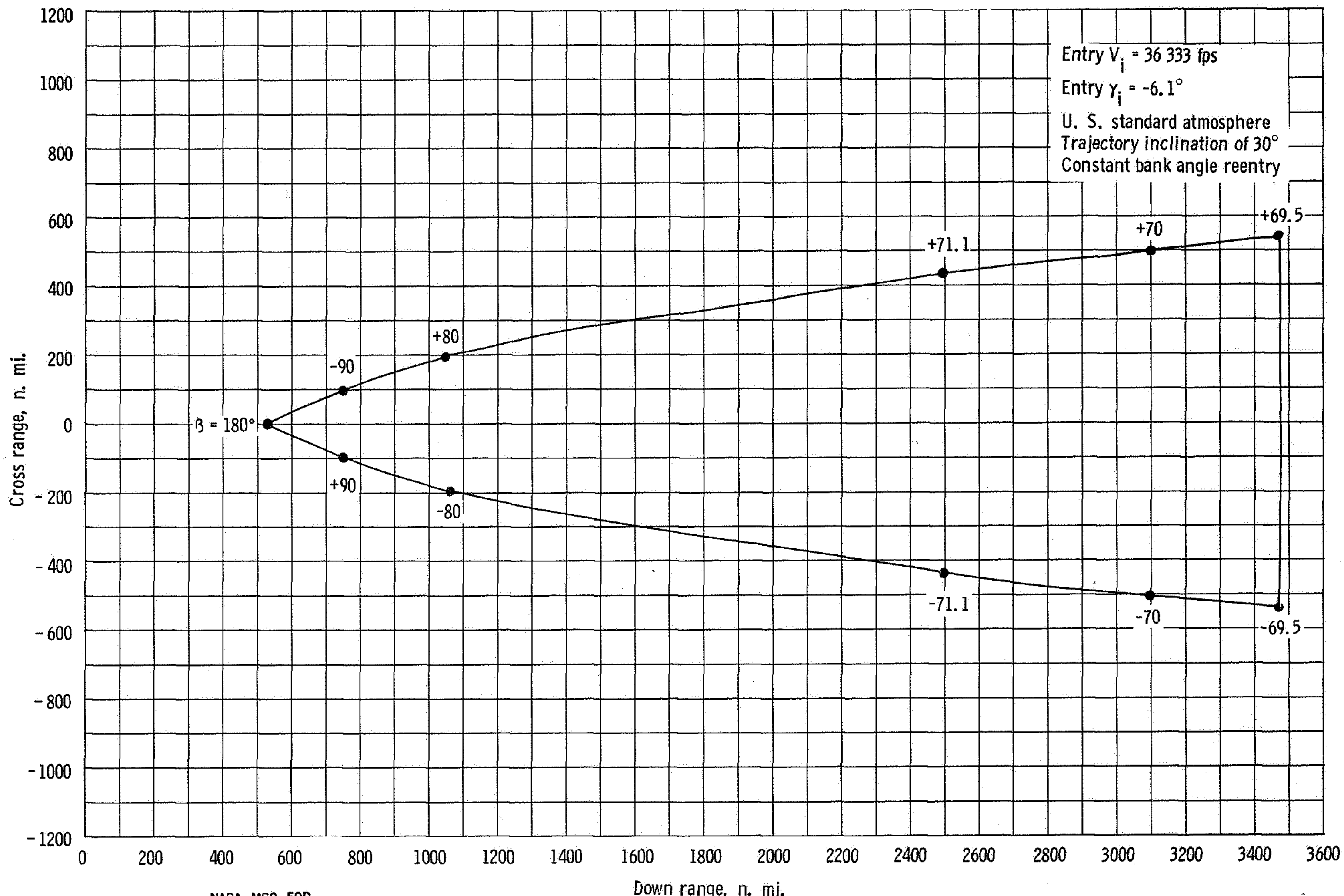
(c) L/D = 0.40, W/C_DA = 64.404.

Figure 1. - Continued.



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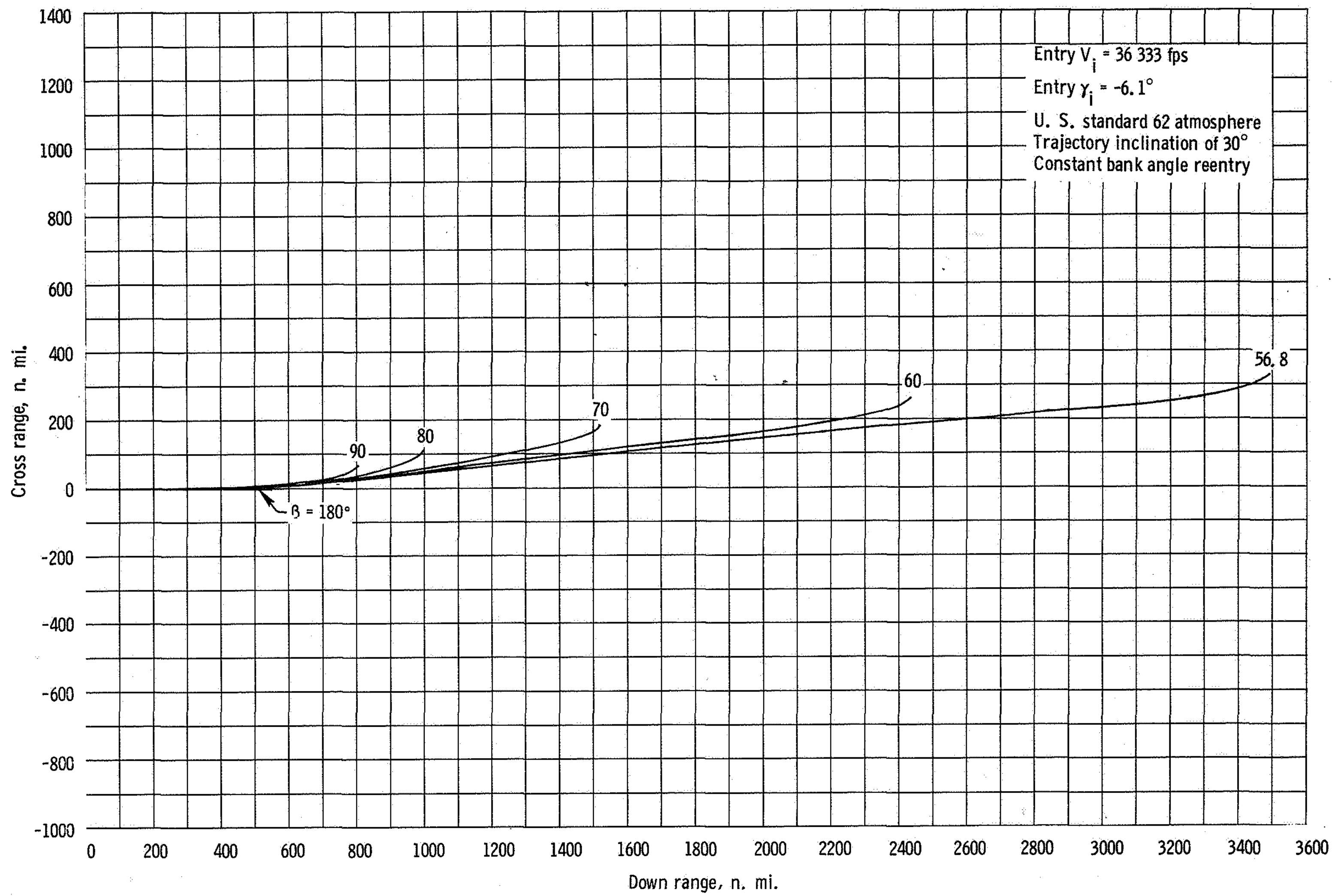
(d) $L/D = 0.45$, $W/C_DA = 72.968$.

Figure 1. - Concluded.



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Plot No. 15,726 (b)
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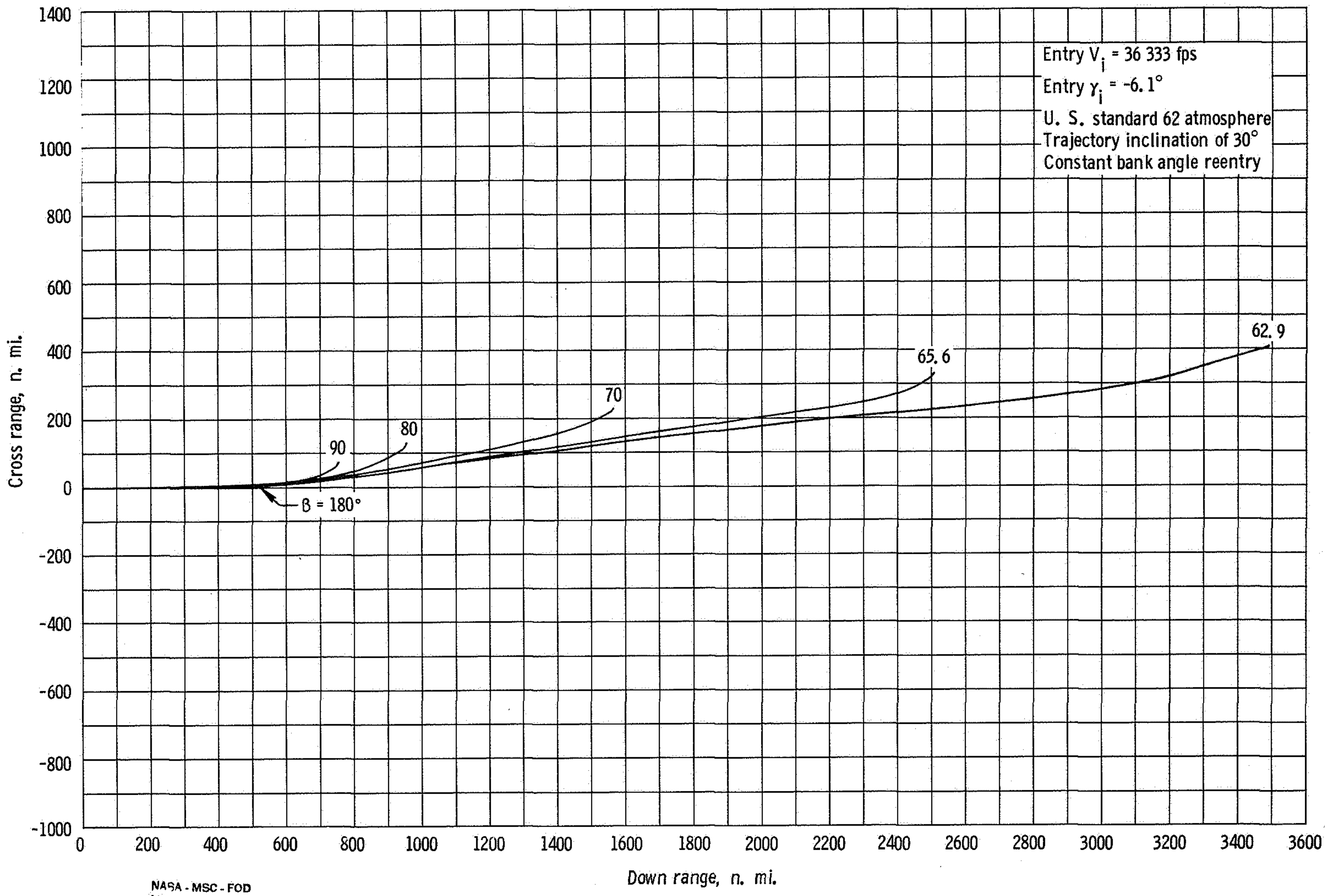
(a) L/D = 0.30, W/C_DA = 69.899.

Figure 2.- Down-range and cross-range profile from reentry.



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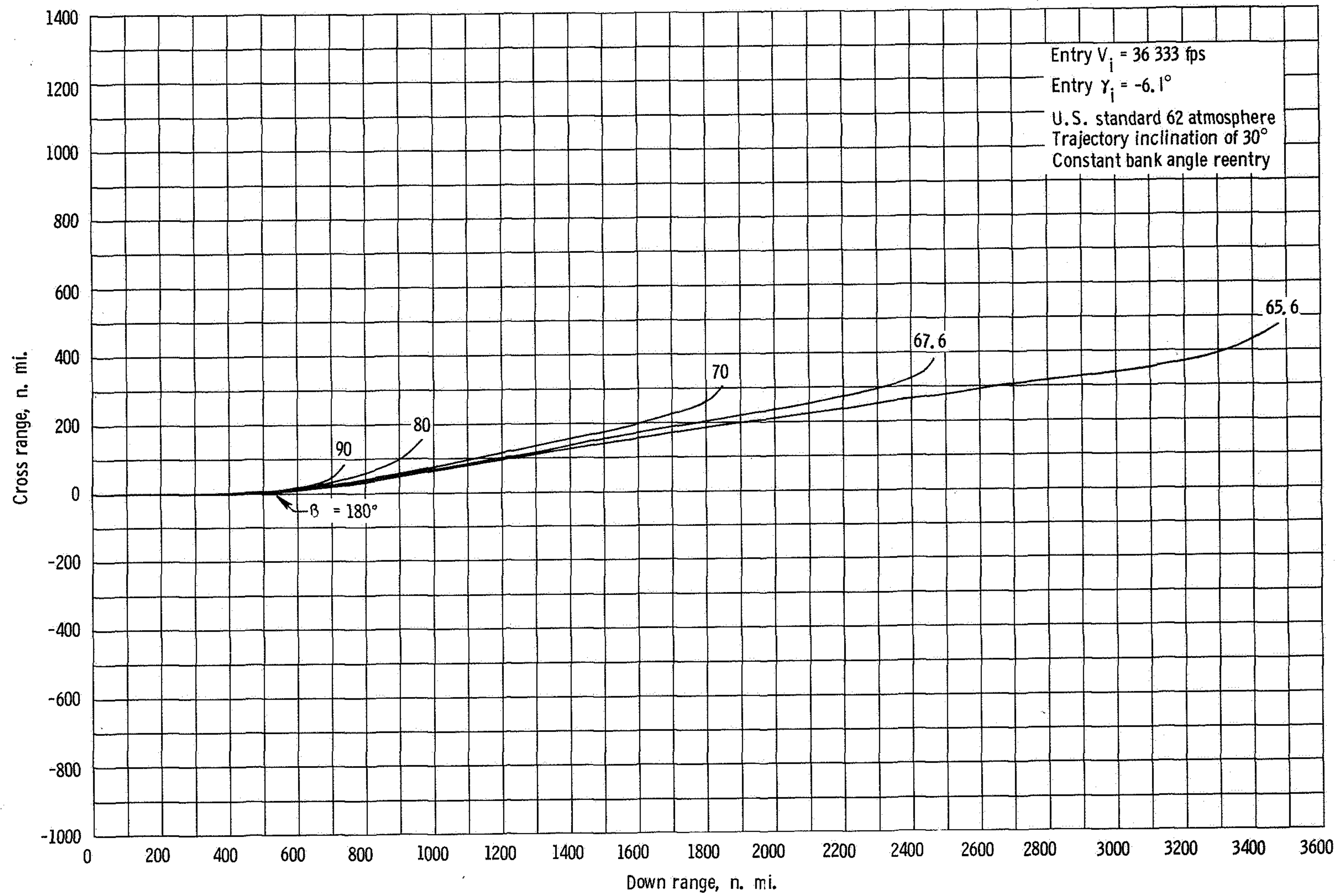
Plot No. 15,727 (b)
Date 6/21/66 W. Scott

(b) L/D = 0.35, W/C_DA = 69.627.

Figure 2. - Continued.



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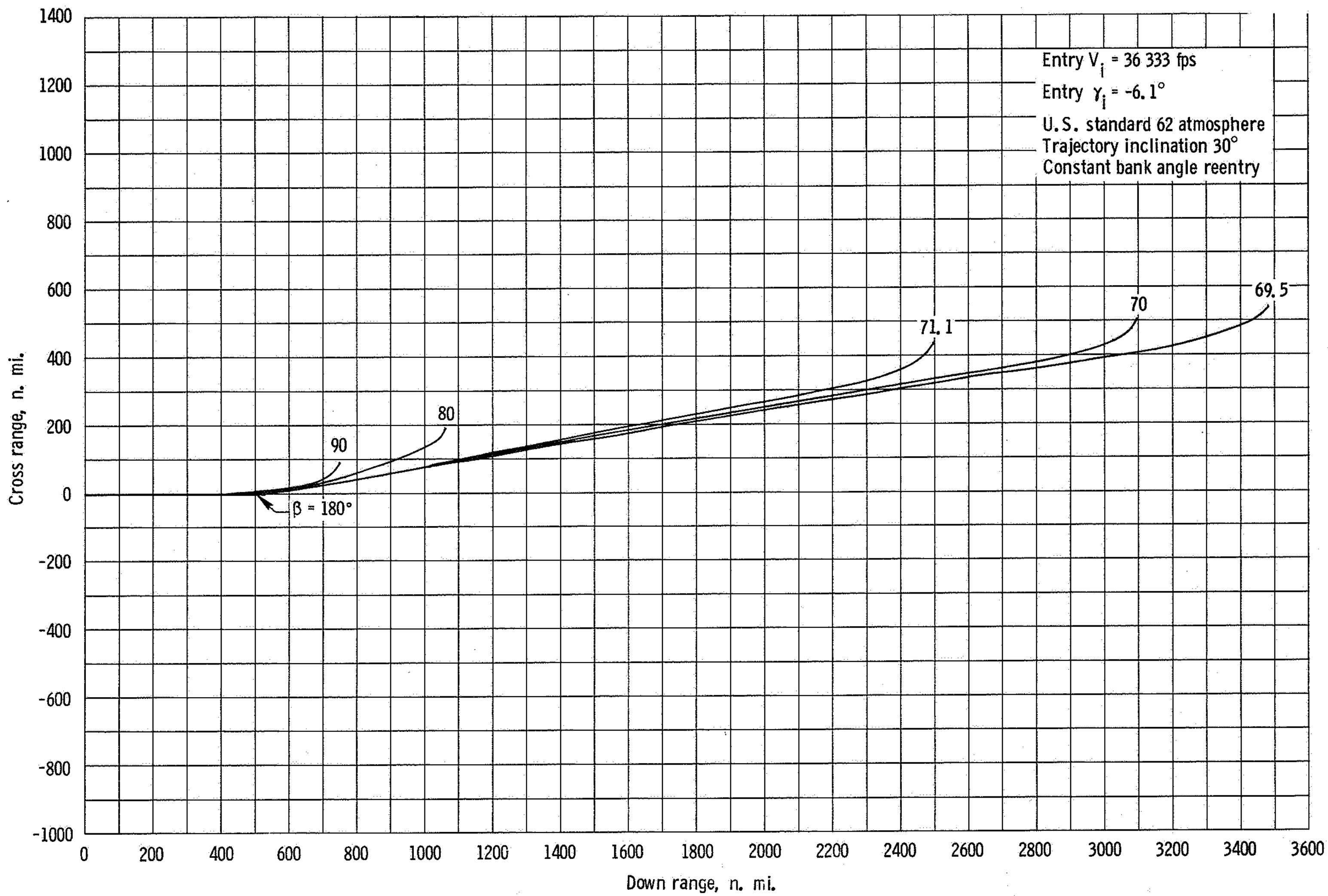
Plot No. 15,728 (t)
Date 6/21/66 W. Scott

(c) L/D = 0.40, W/C_DA = 64.404.

Figure 2. - Continued.



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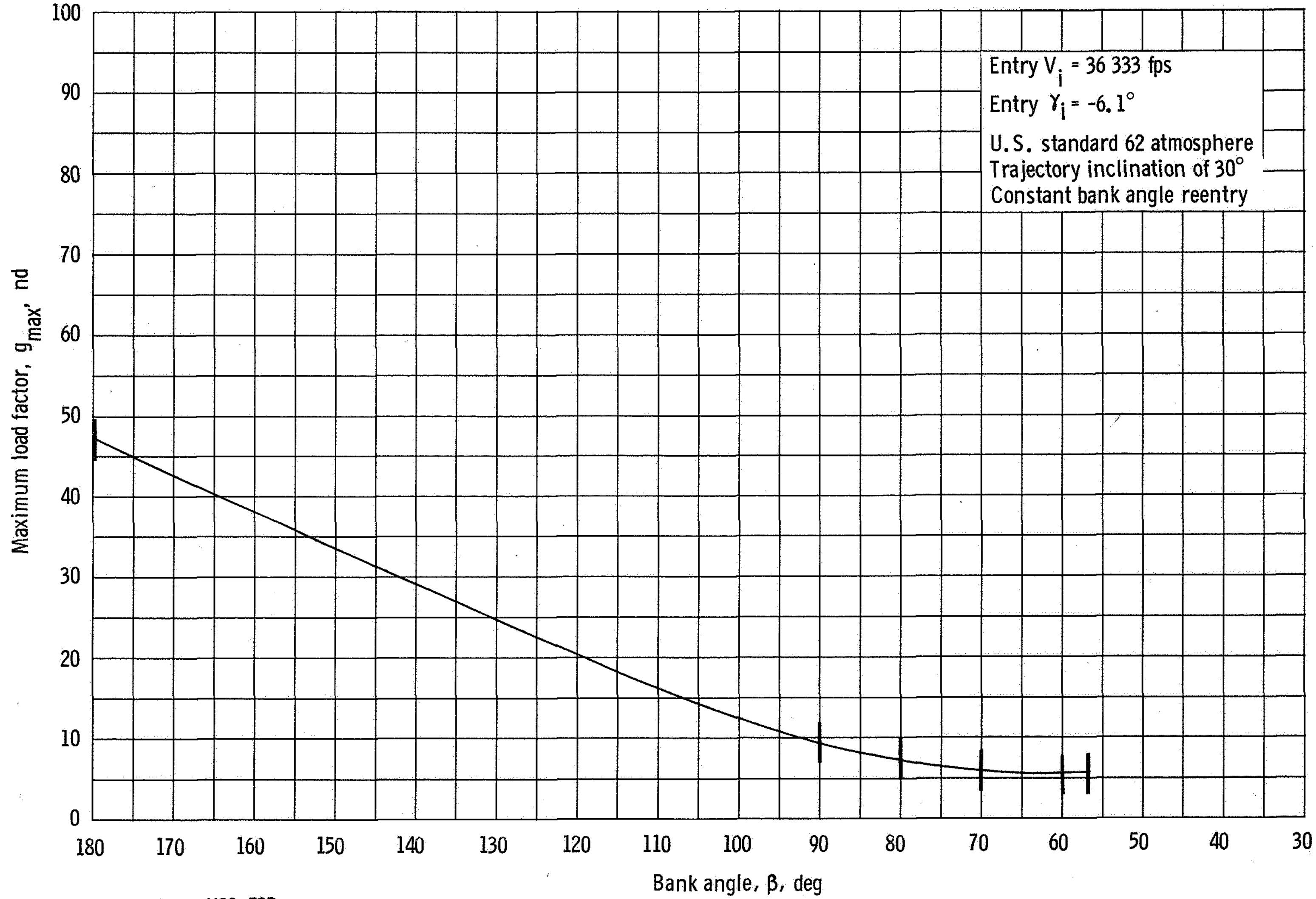
Plot No. 15,729 (c)
Date 6/21/66 W. Scott

(d) $L/D = 0.45$, $W/C_DA = 72.968$.

Figure 2. - Concluded.



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Plot No. 15,726 (c)
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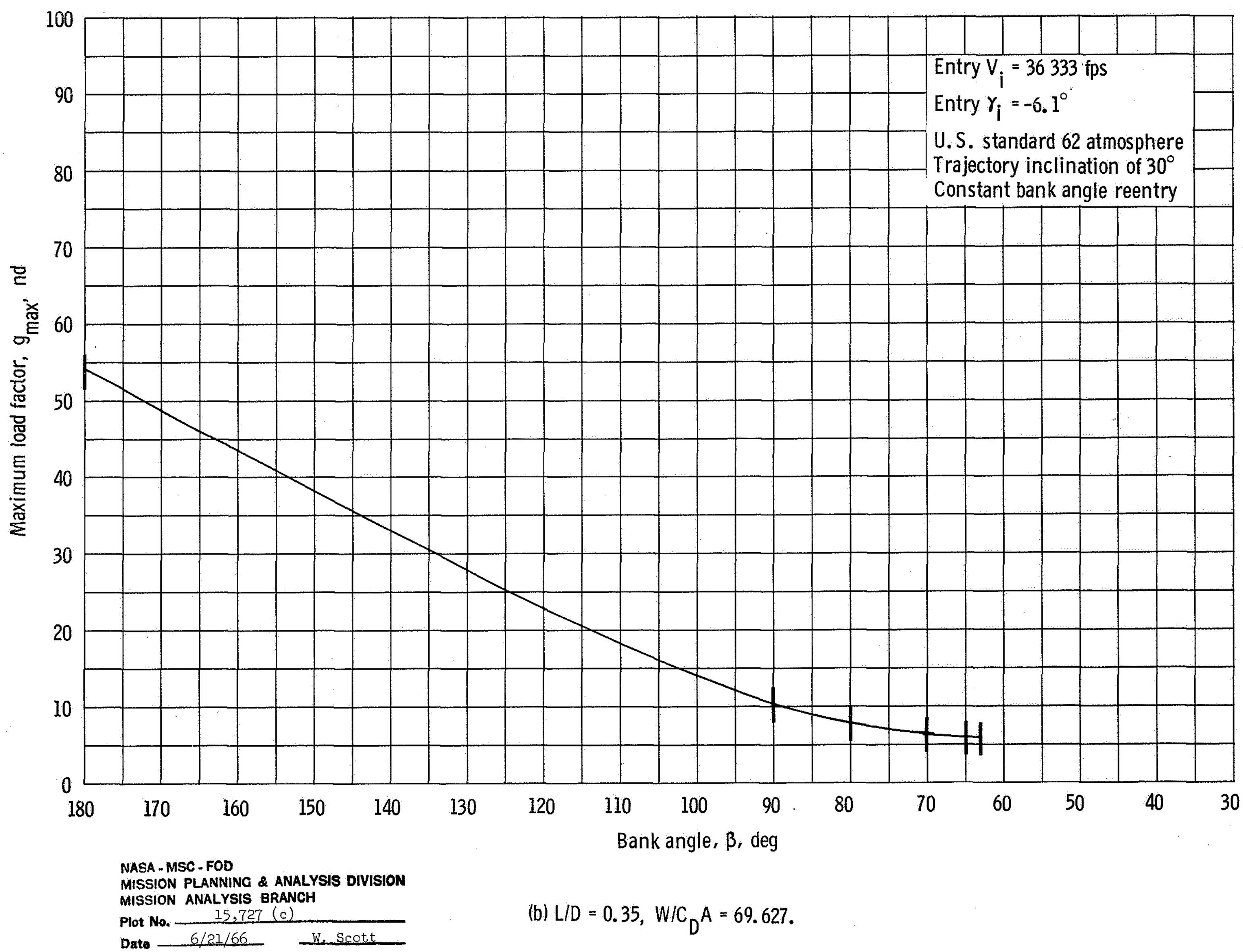
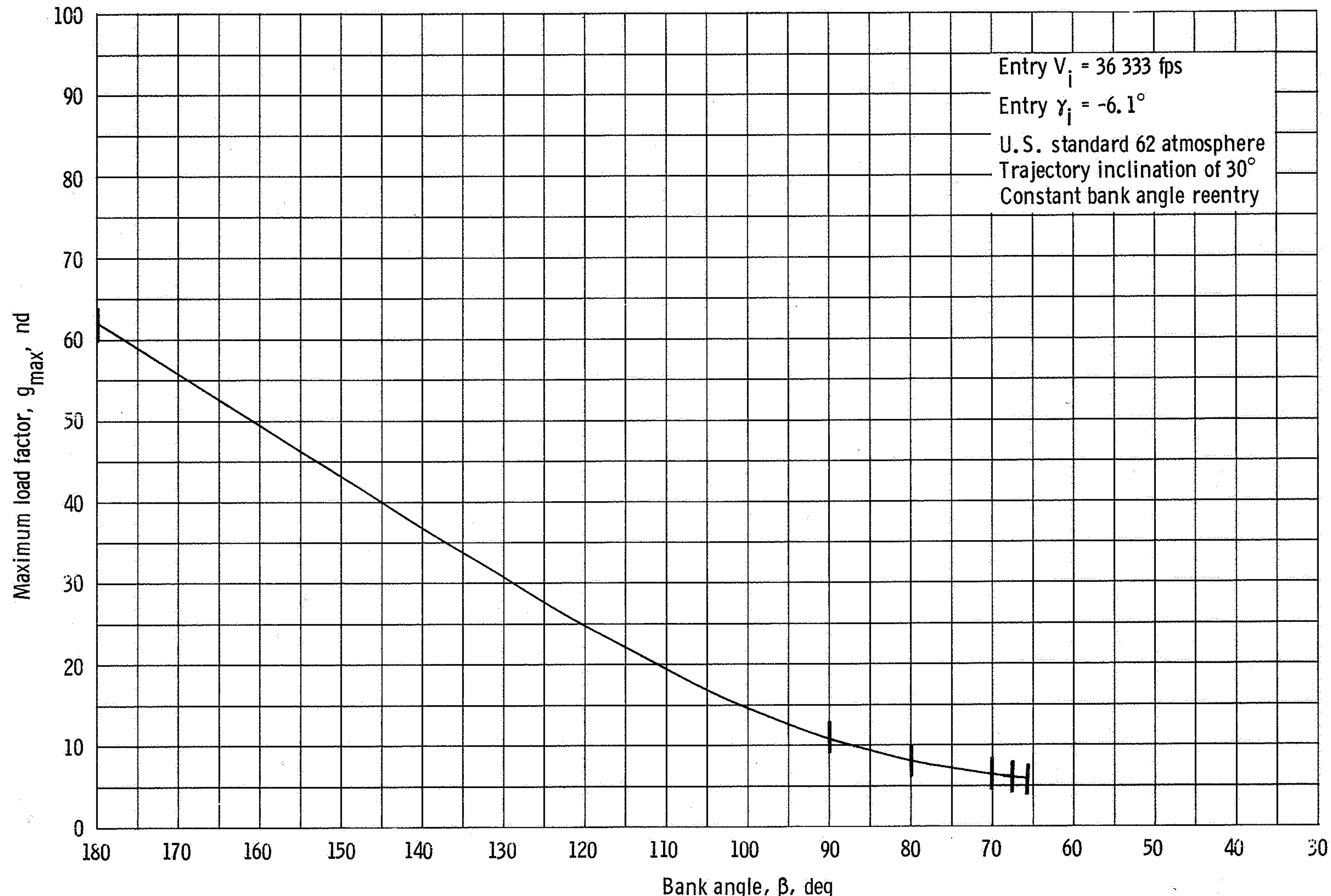
(a) L/D = 0.30, W/C_DA = 69.899.

Figure 3. - Maximum load factor versus bank angle.



(b) L/D = 0.35, W/C_DA = 69.627.

Figure 3. - Continued.



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Plot No. 15,728 (c)
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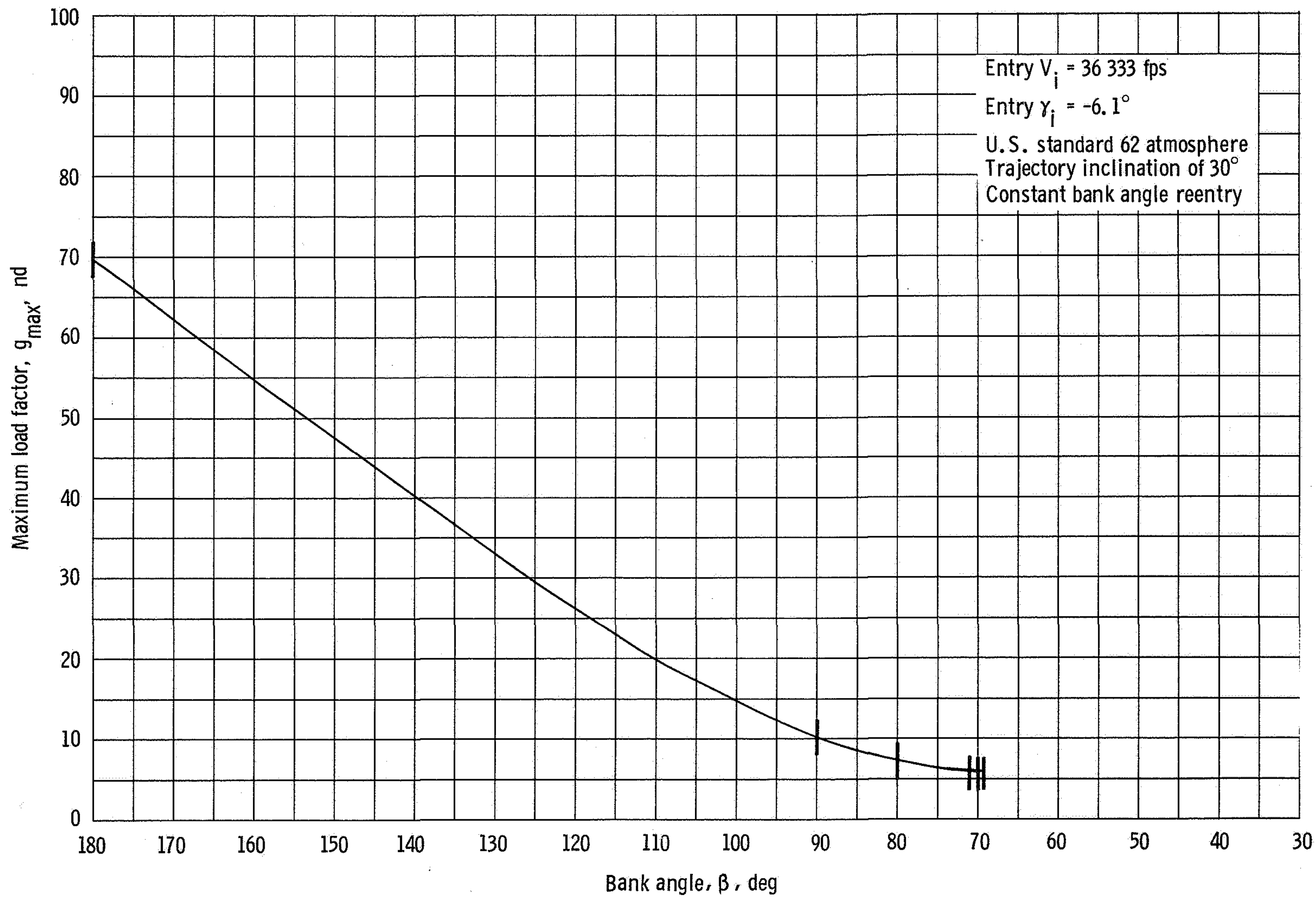
(c) L/D = 0.40, W/C_DA = 64.404.

Figure 3. - Continued.



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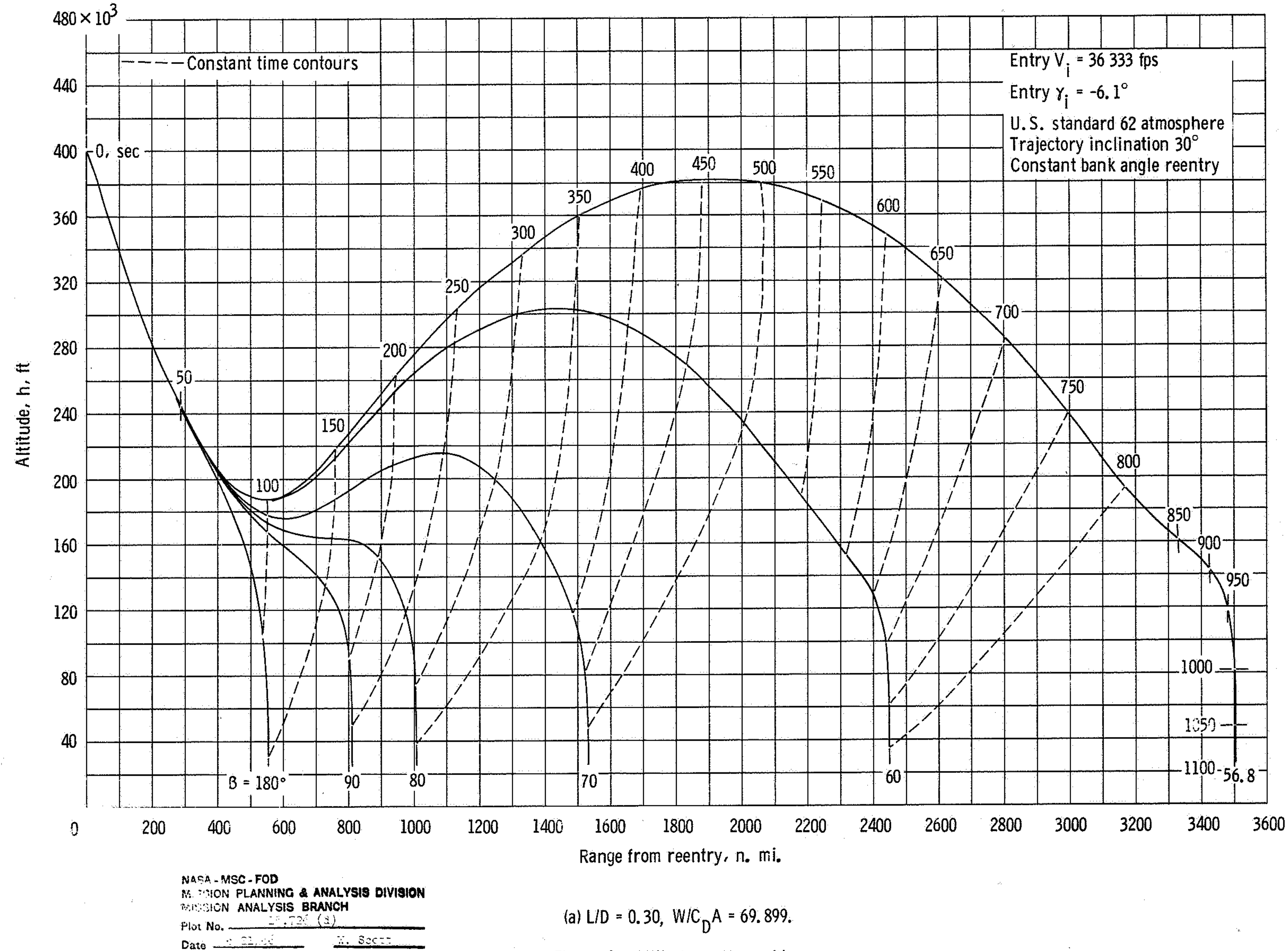
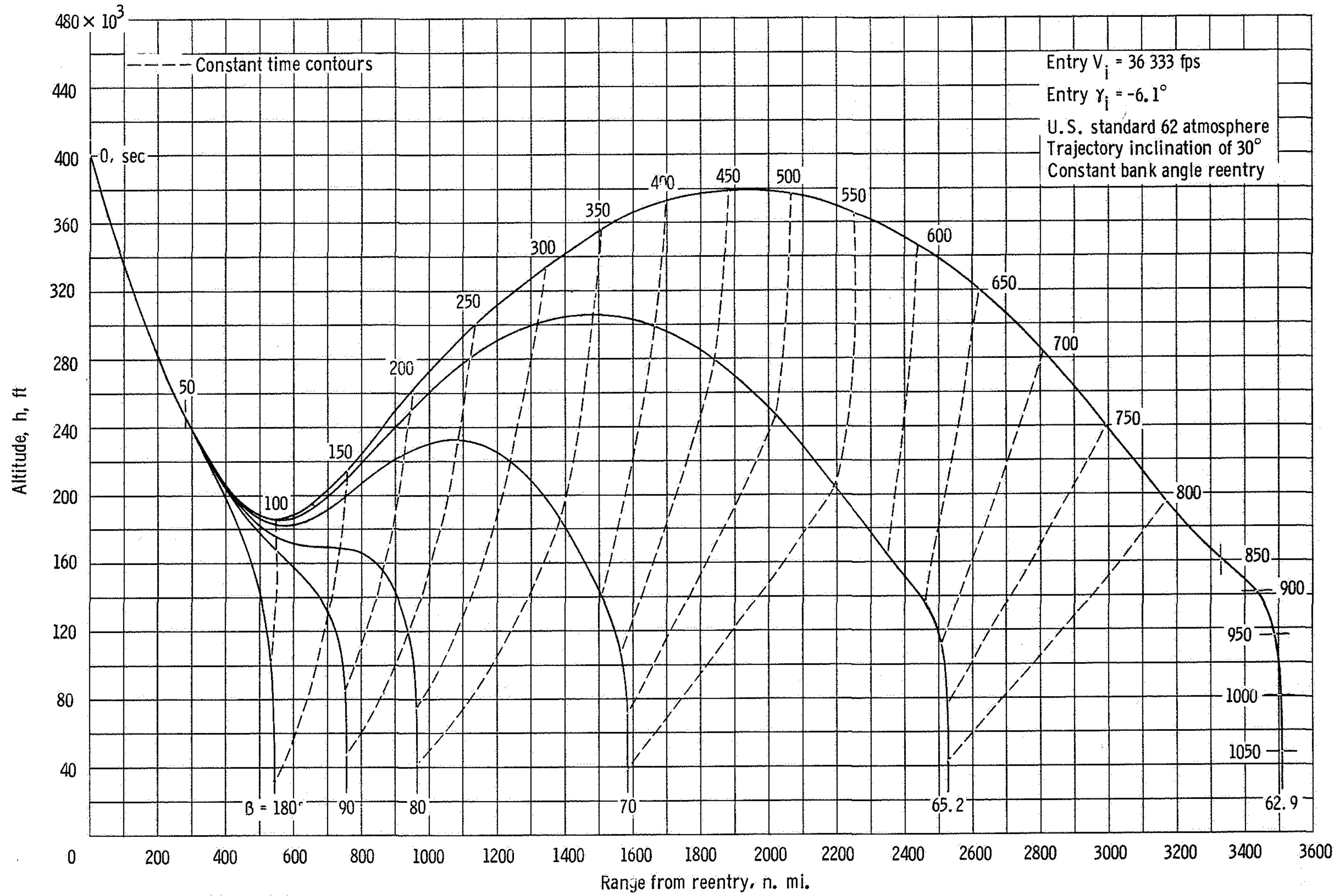
(d) $L/D = 0.45$, $W/C_DA = 72.968$.

Figure 3. - Concluded.



(a) L/D = 0.30, W/C_DA = 69.899.

Figure 4. - Altitude-range profiles.



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Plot No. 15,727 (d)
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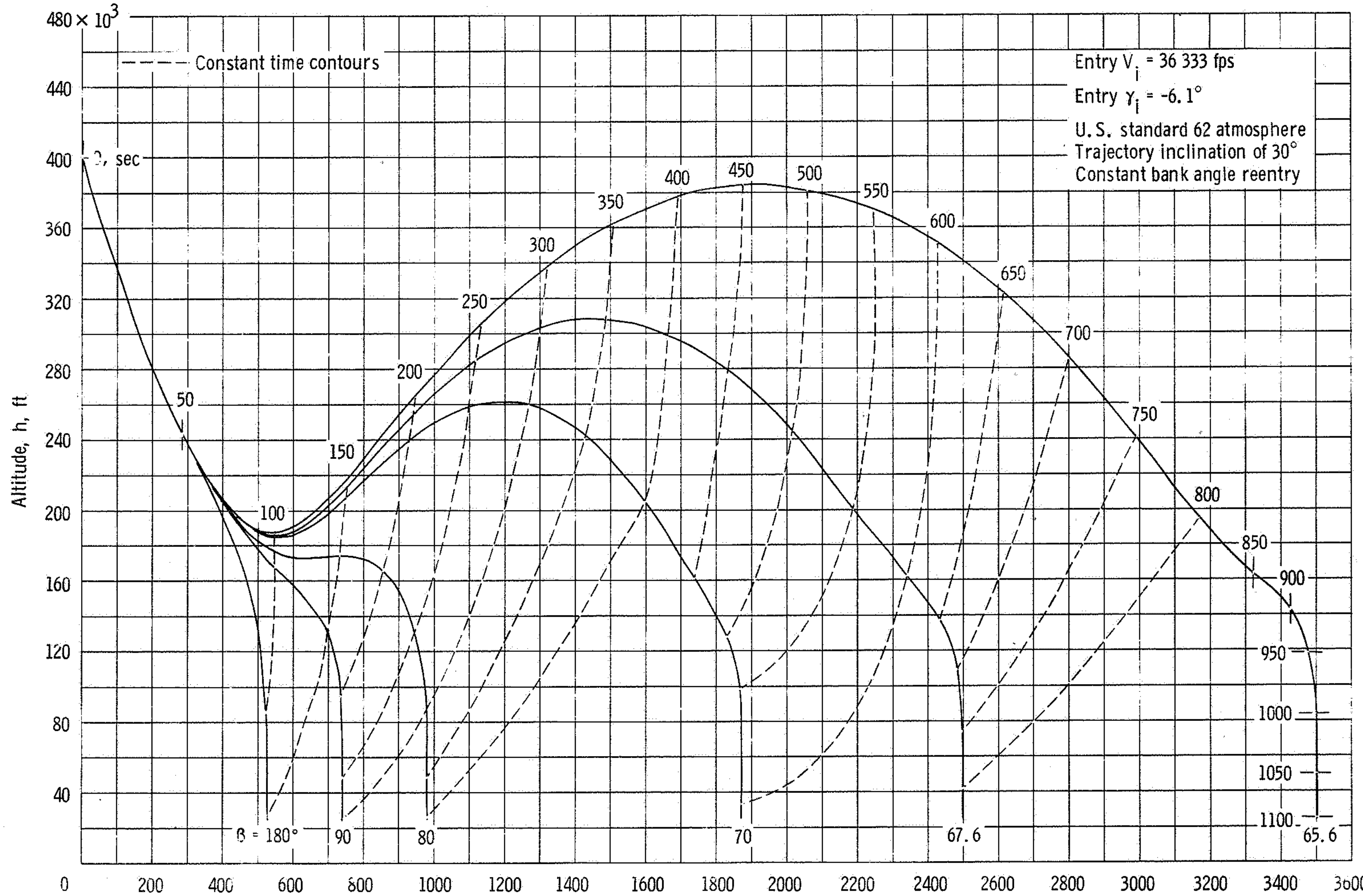
(b) L/D = 0.35, W/C_DA = 69.627.

Figure 4. - Continued.



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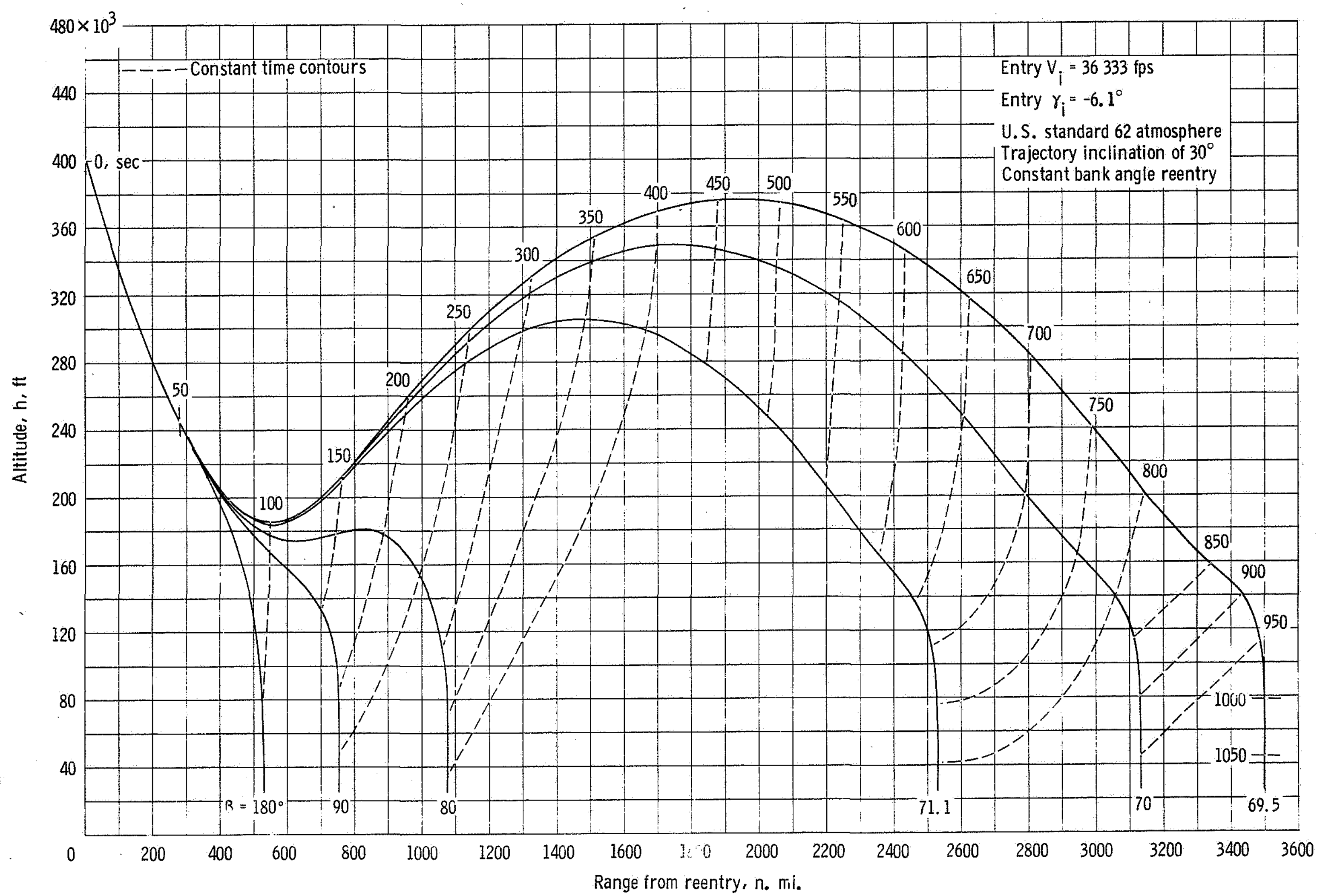
(c) L/D = 0.40, W/C_DA = 64.404.

Figure 4. - Continued.



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Plot No. 15.7-5 (d)
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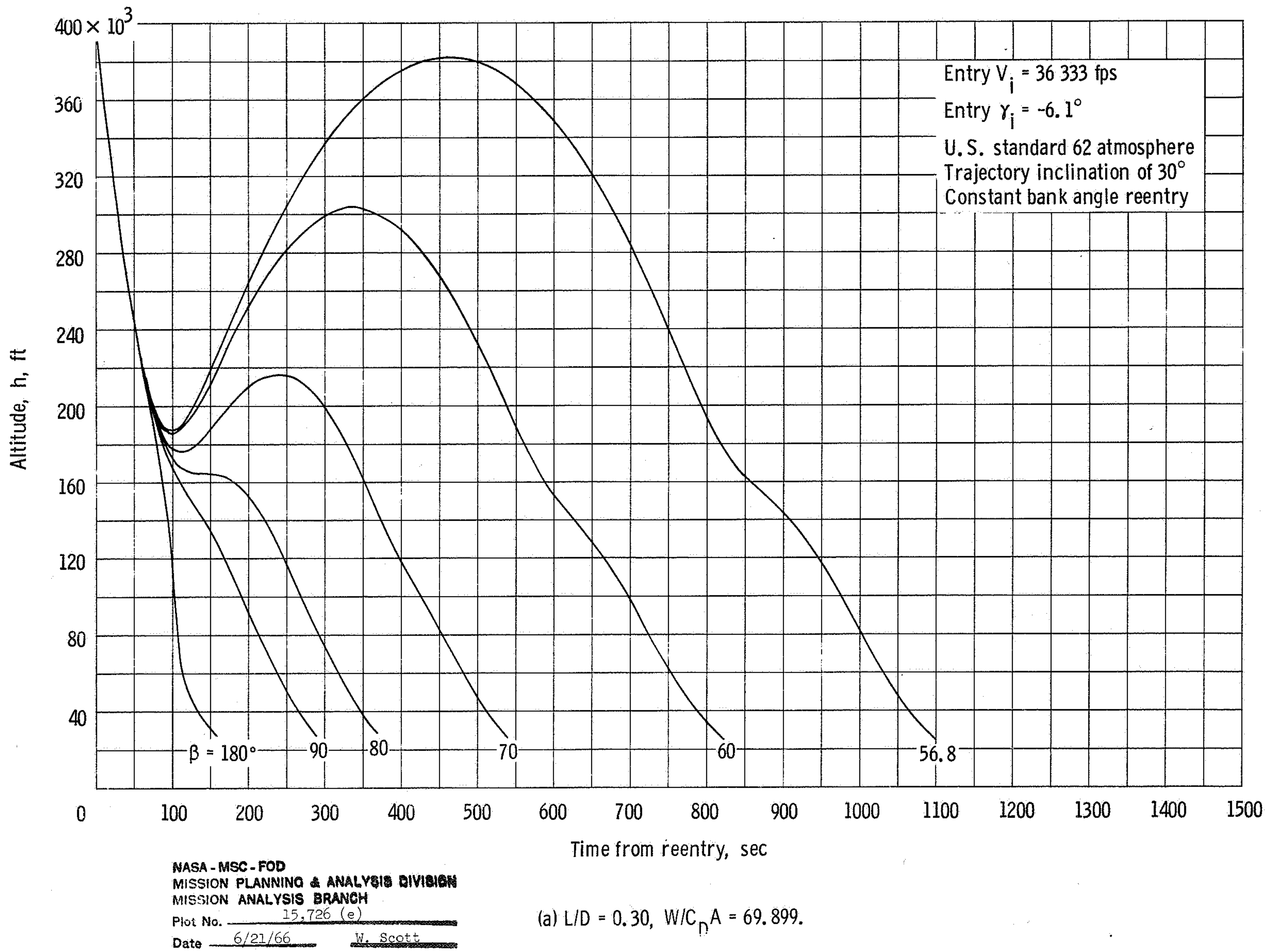
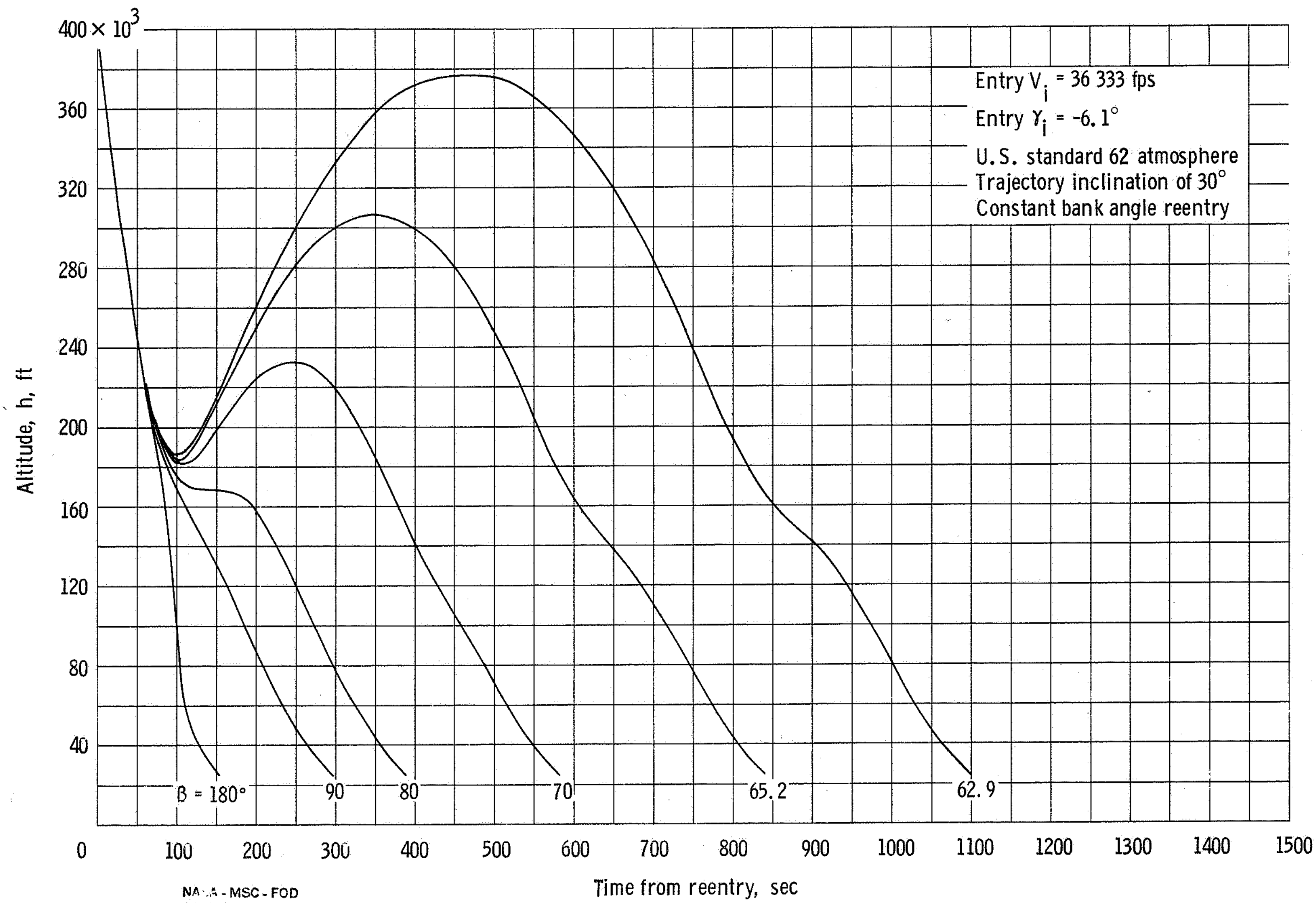
(d) L/D = 0.45, W/C_DA = 72.968.

Figure 4. - Concluded.



(a) $L/D = 0.30$, $W/C_D A = 69.899$.

Figure 5. - Altitude versus time.



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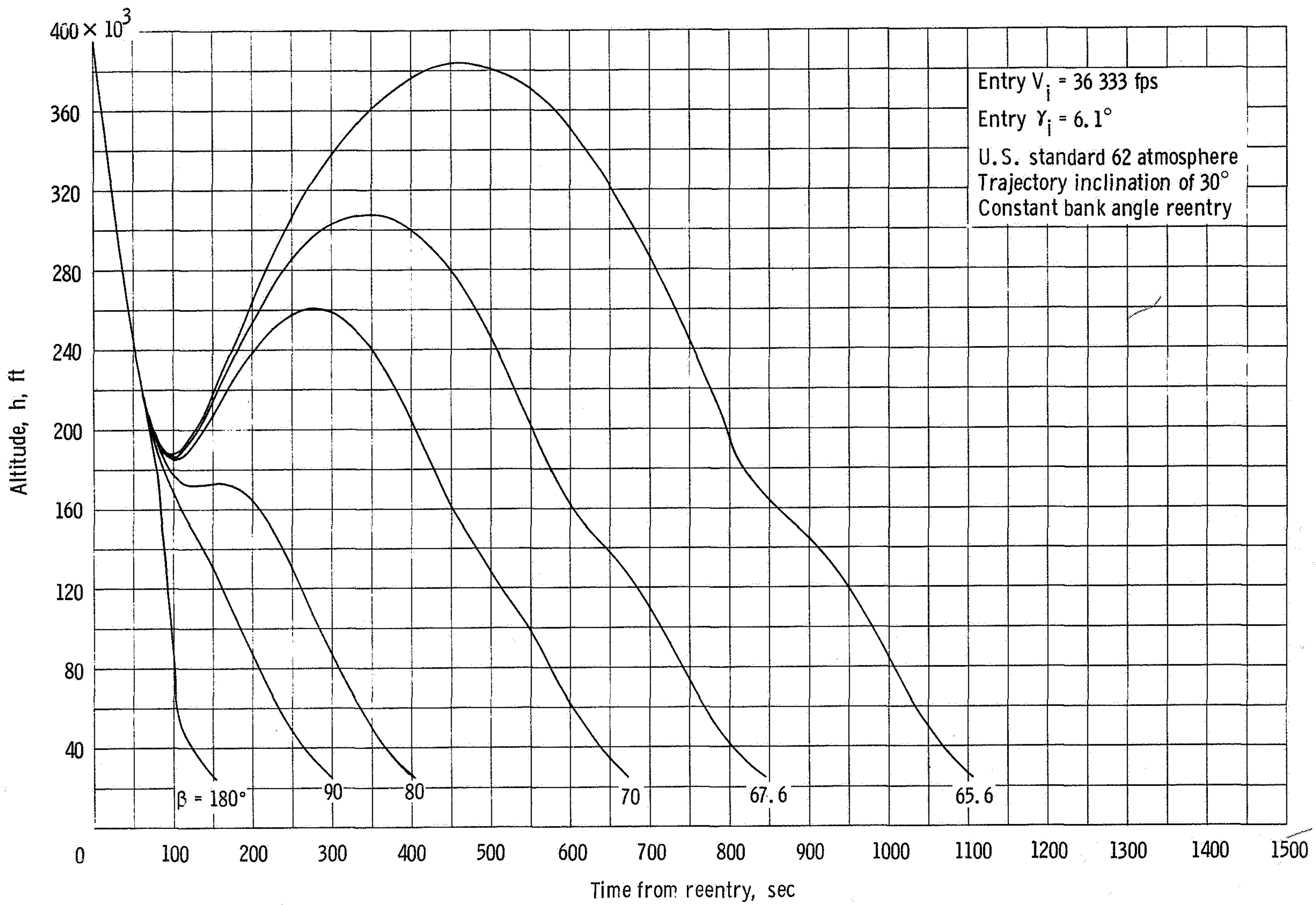
(b) $L/D = 0.35$, $W/C_DA = 69.627$.

Figure 5. - Continued.



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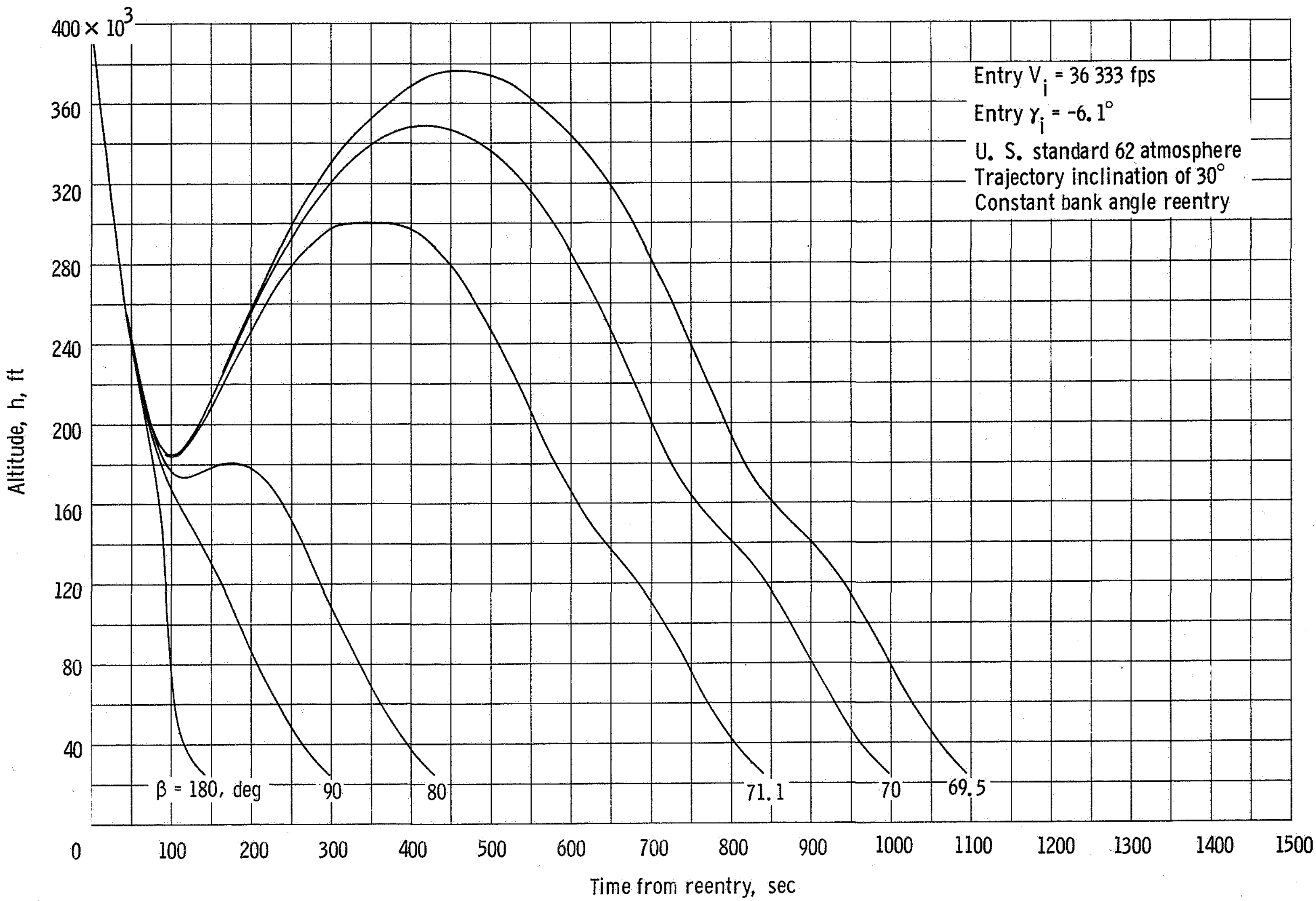
(c) $L/D = 0.40$, $W/C_DA = 64.404$.

Figure 5. - Continued.



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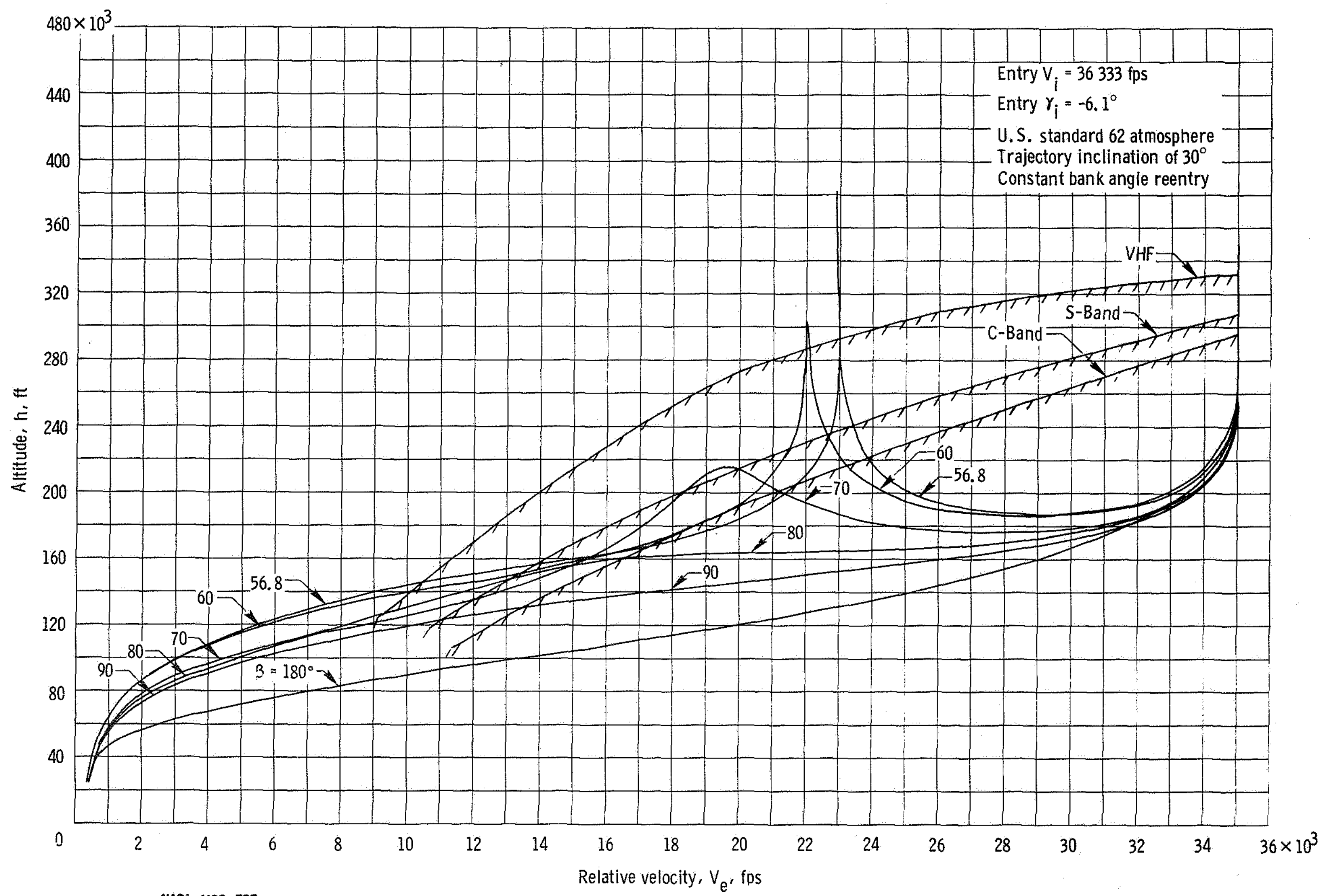
(d) L/D = 0.45, W/C_DA = 72.968.

Figure 5. - Concluded.



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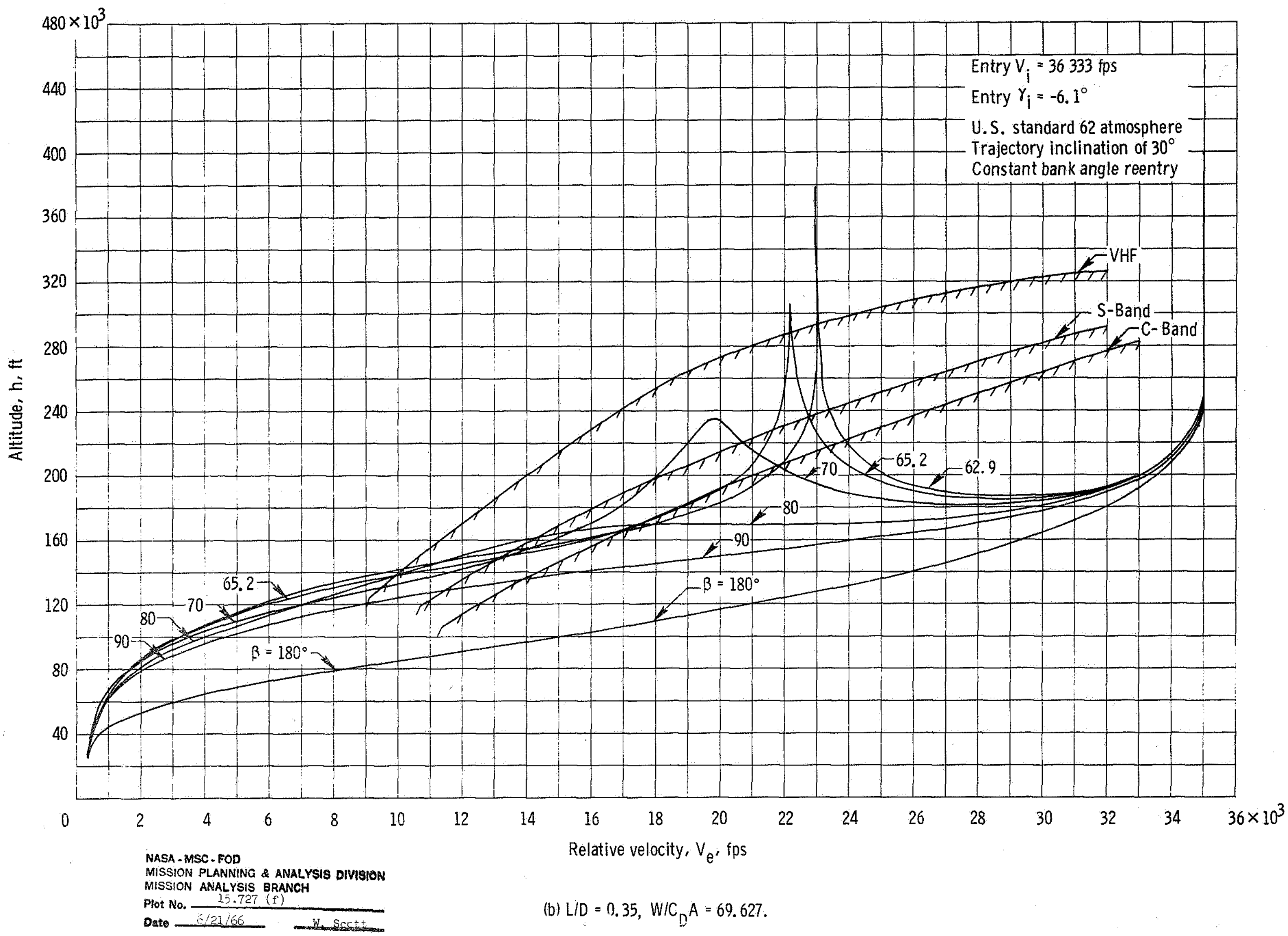
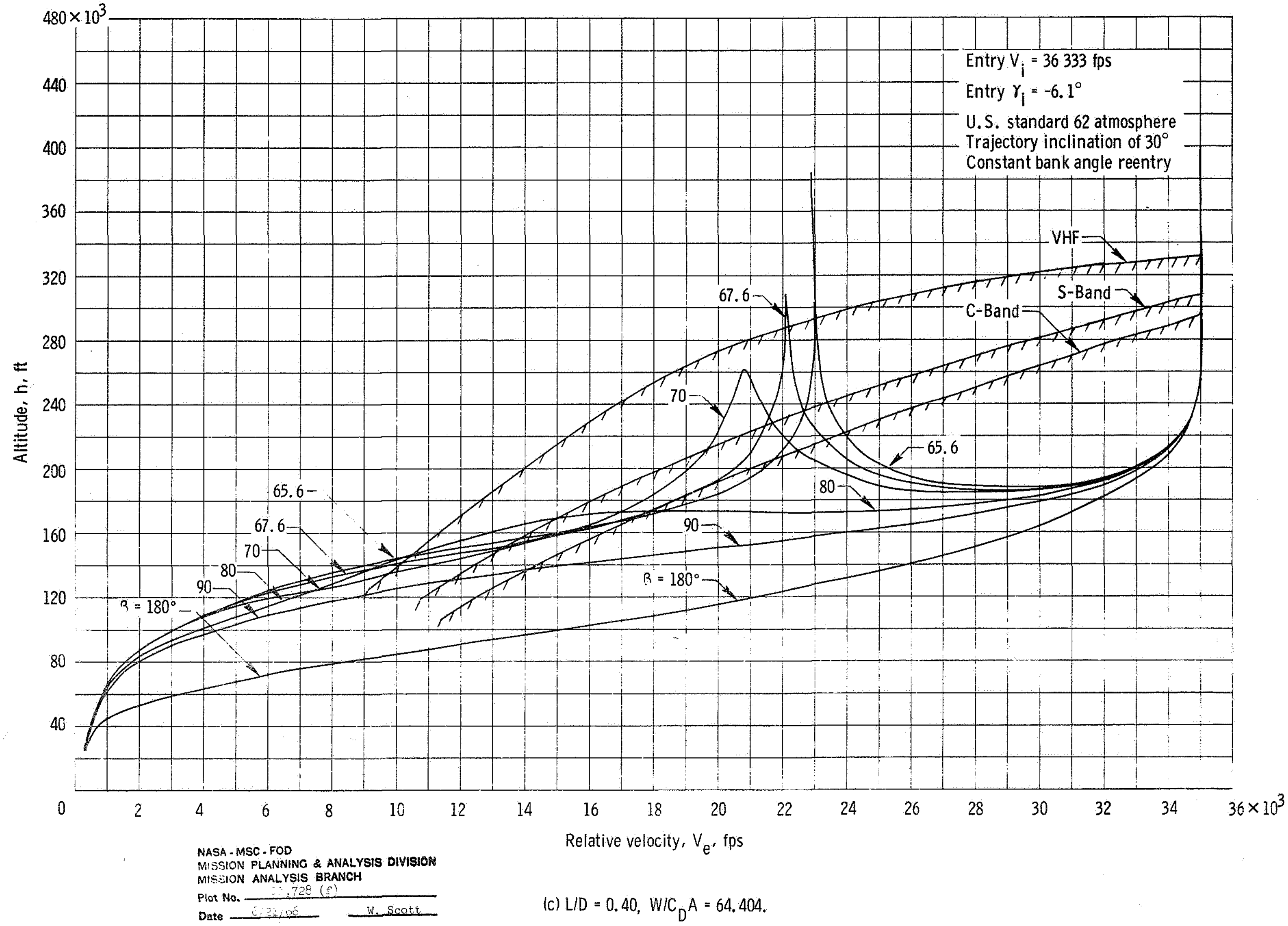
(a) L/D = 0.30, W/C_DA = 69.899.

Figure 6. - Altitude versus relative velocity.



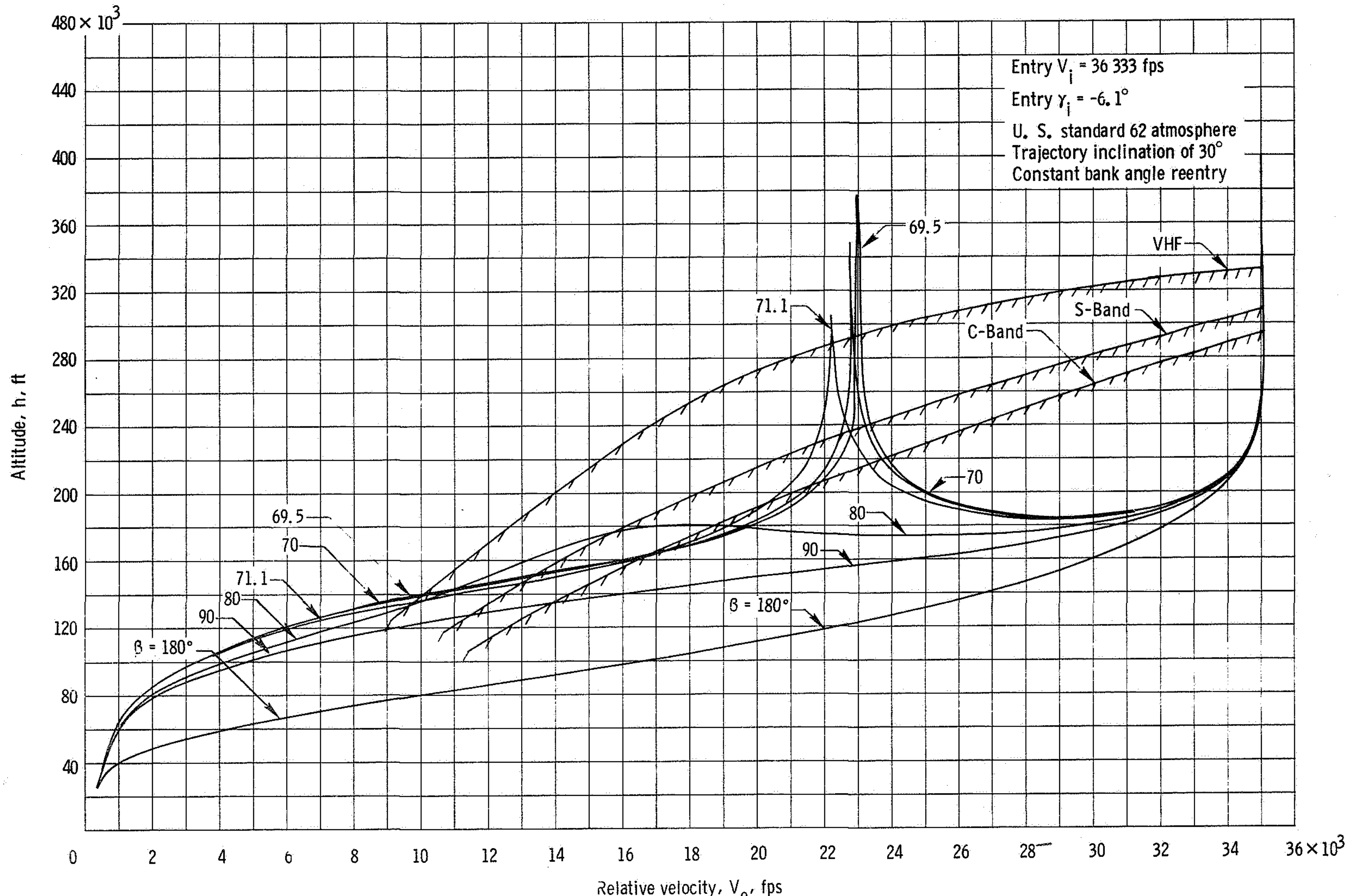
(b) L/D = 0.35, W/C_DA = 69.627.

Figure 6. - Continued.



(c) L/D = 0.40, W/C_DA = 64.404.

Figure 6. - Continued.



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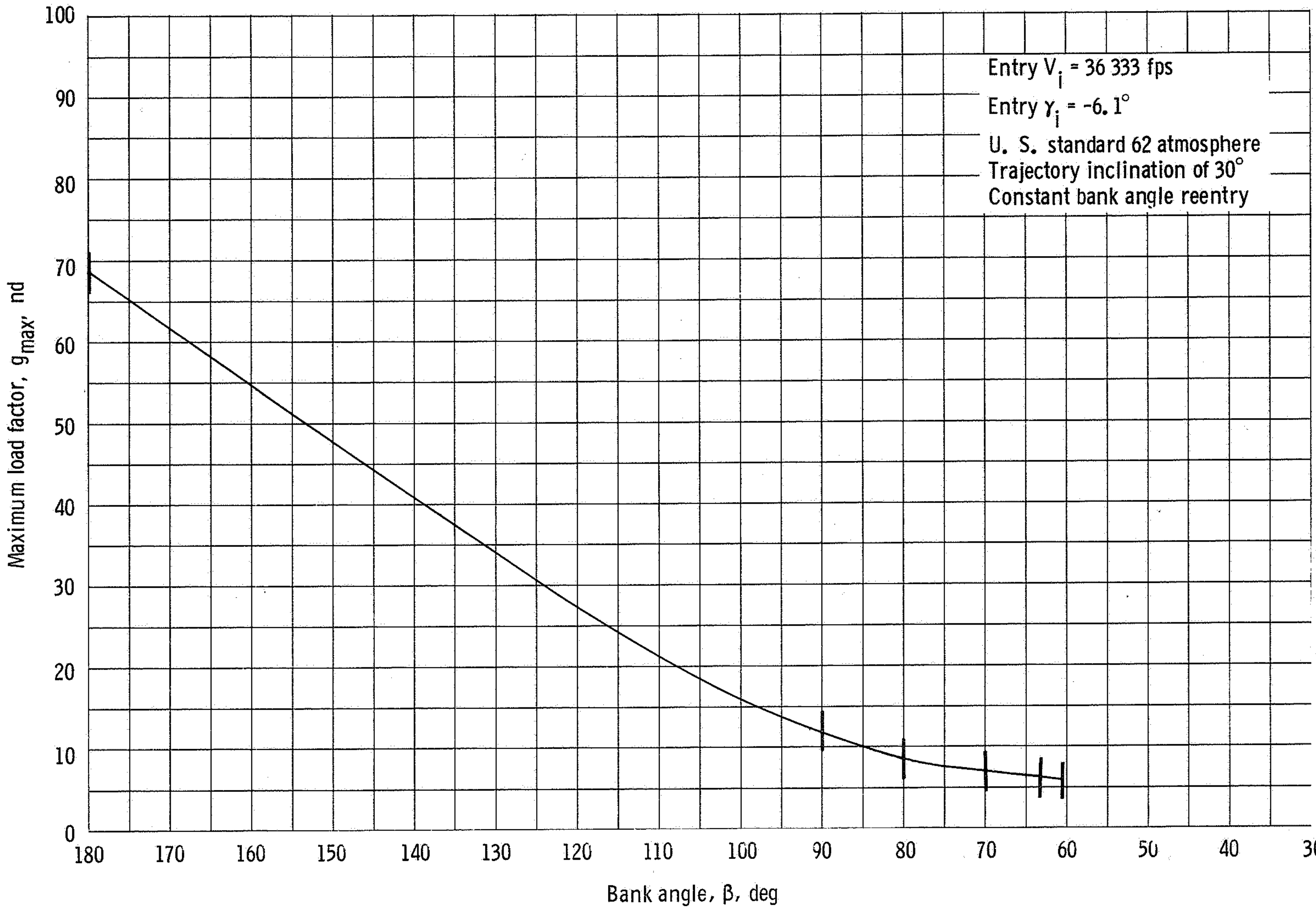
(d) $L/D = 0.45$, $W/C_DA = 72.968$.

Figure 6. - Concluded.



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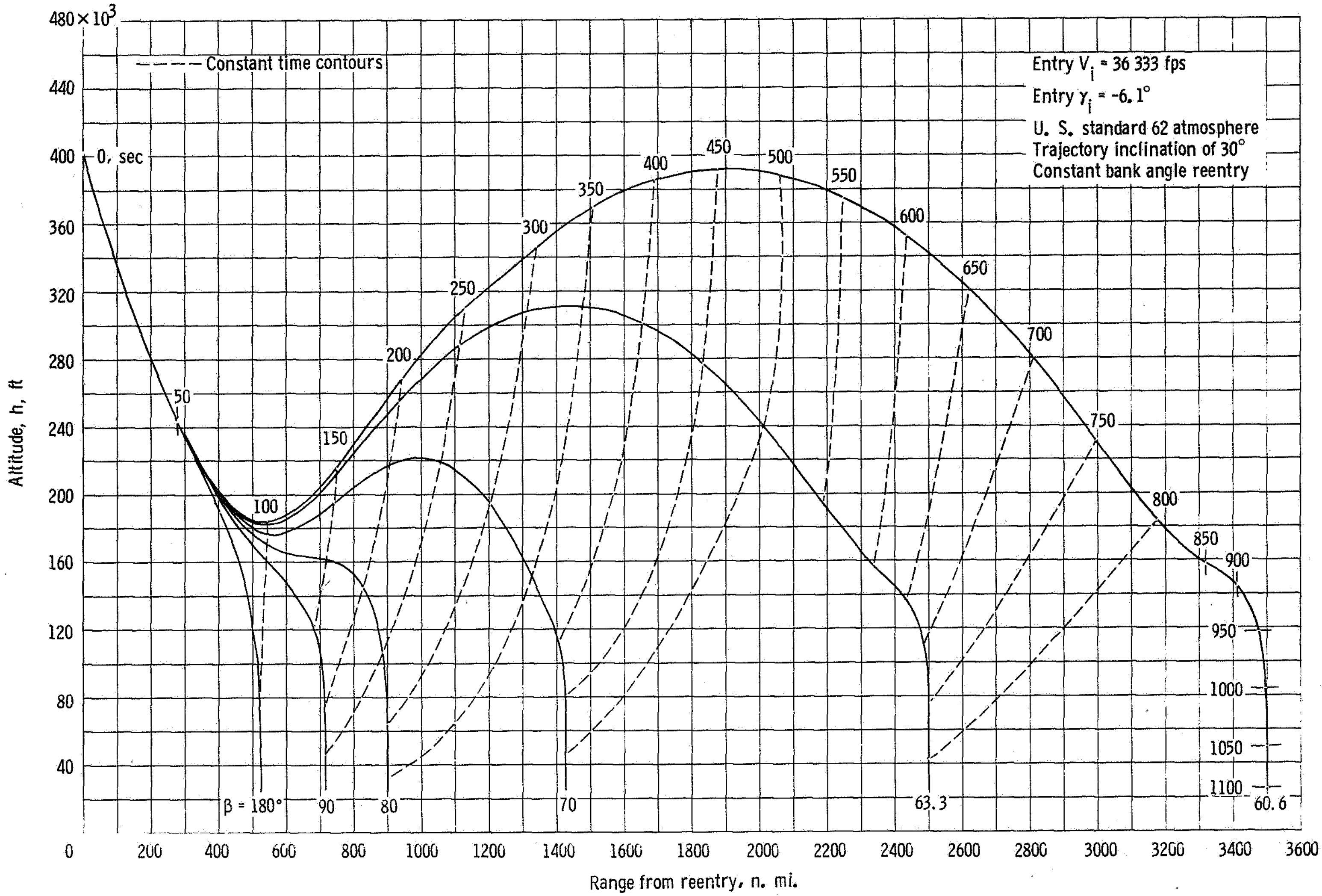
(a) Maximum load factor versus bank angle.

Figure 7. - High-speed reentries.



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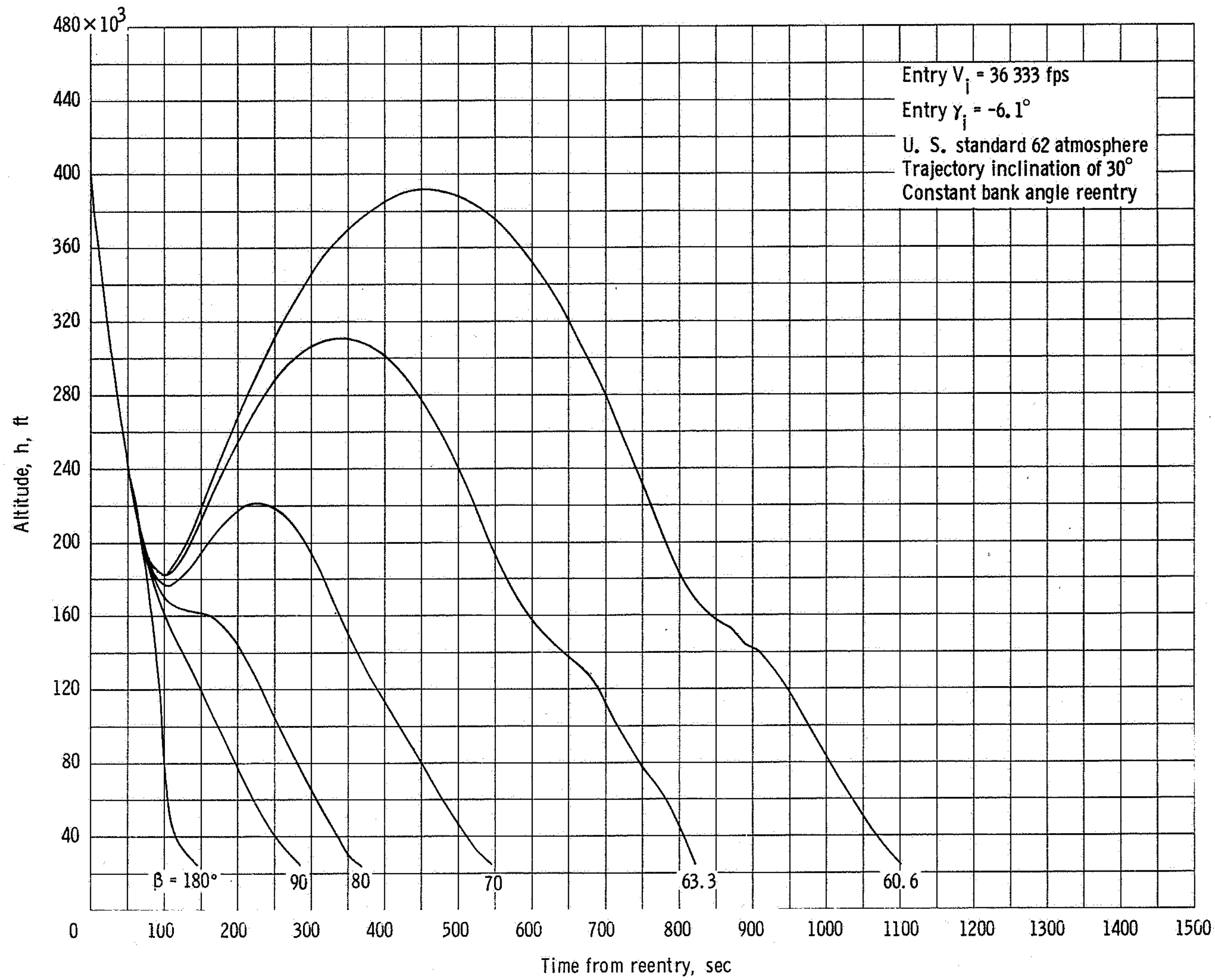
(b) Altitude-range profiles.

Figure 7.- Continued.



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Plot No. 15,769 (c)
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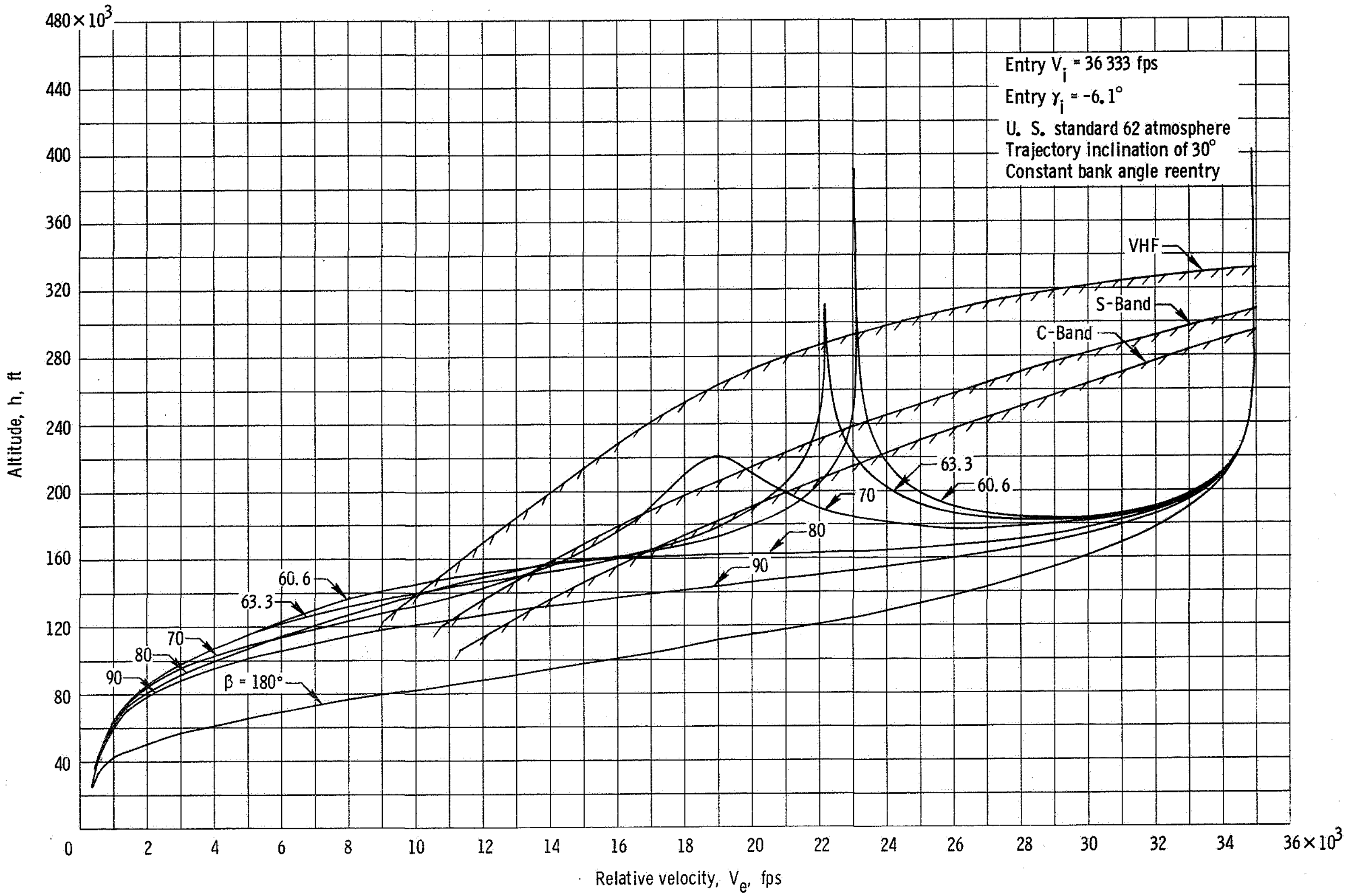
(c) Altitude versus time.

Figure 7. - Continued.



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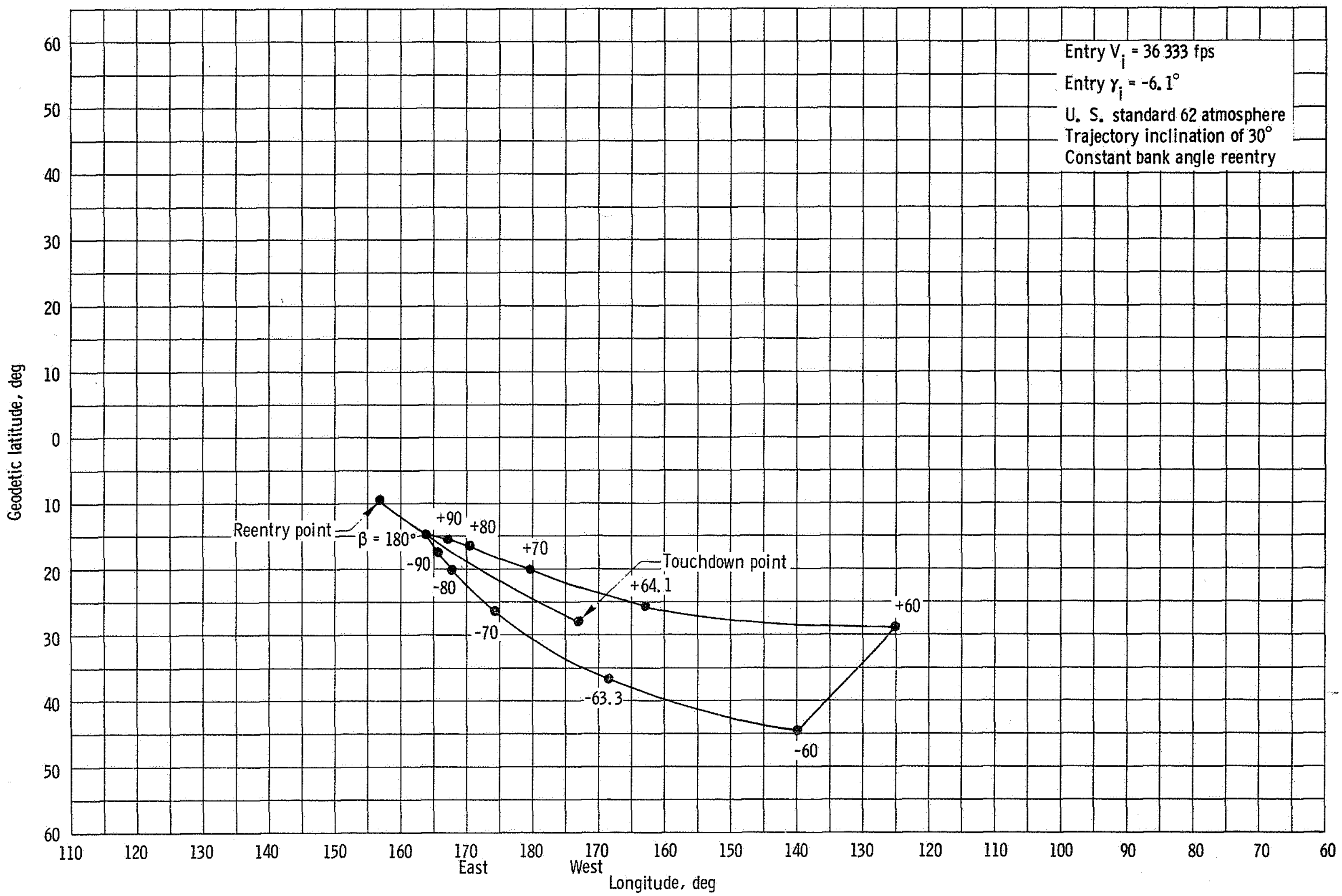
(d) Altitude versus relative velocity.

Figure 7. - Continued.



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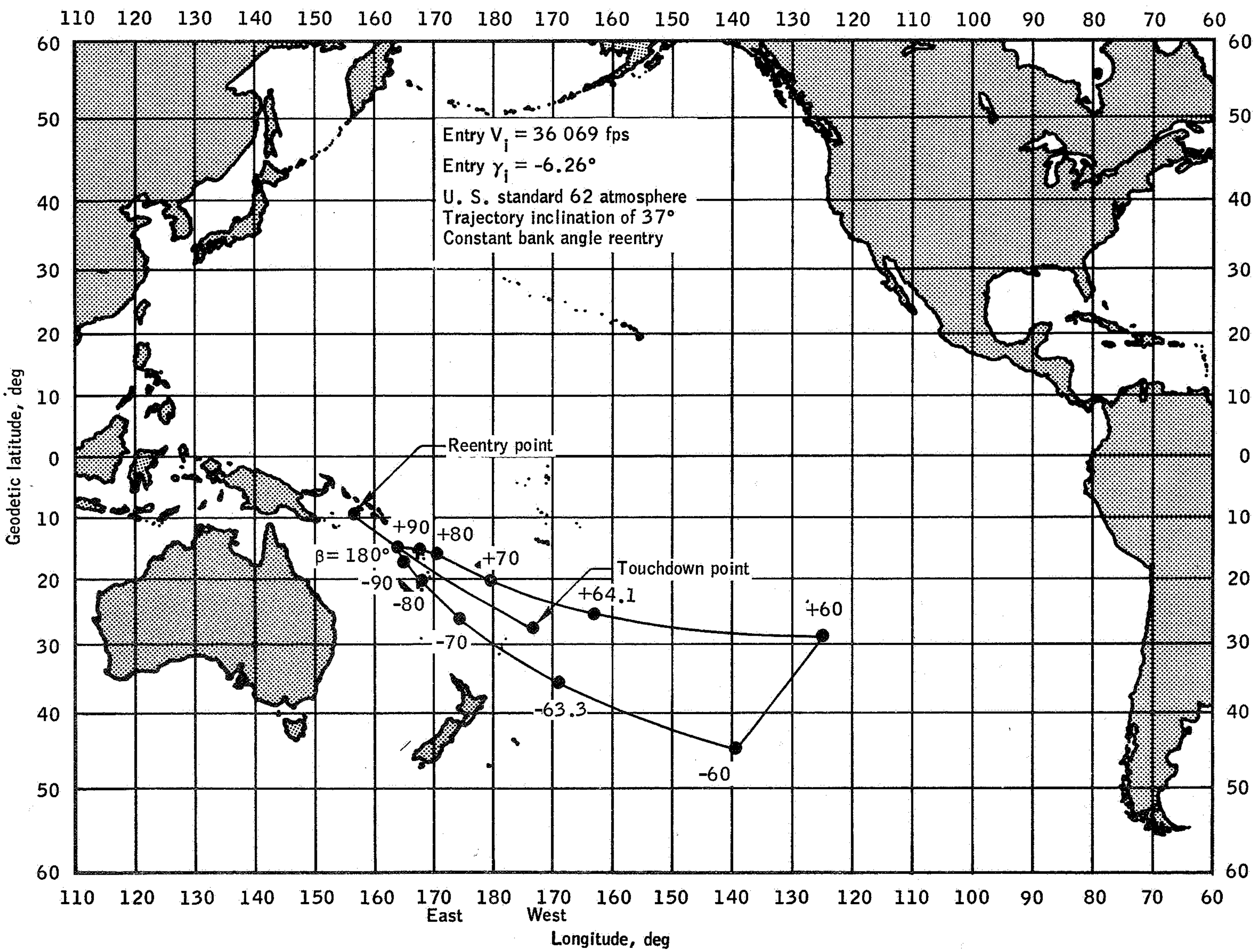
(e) AS-504 footprint.

Figure 7. - Continued.



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(f) AS-504 footprint on map.

Figure 7.- Concluded.

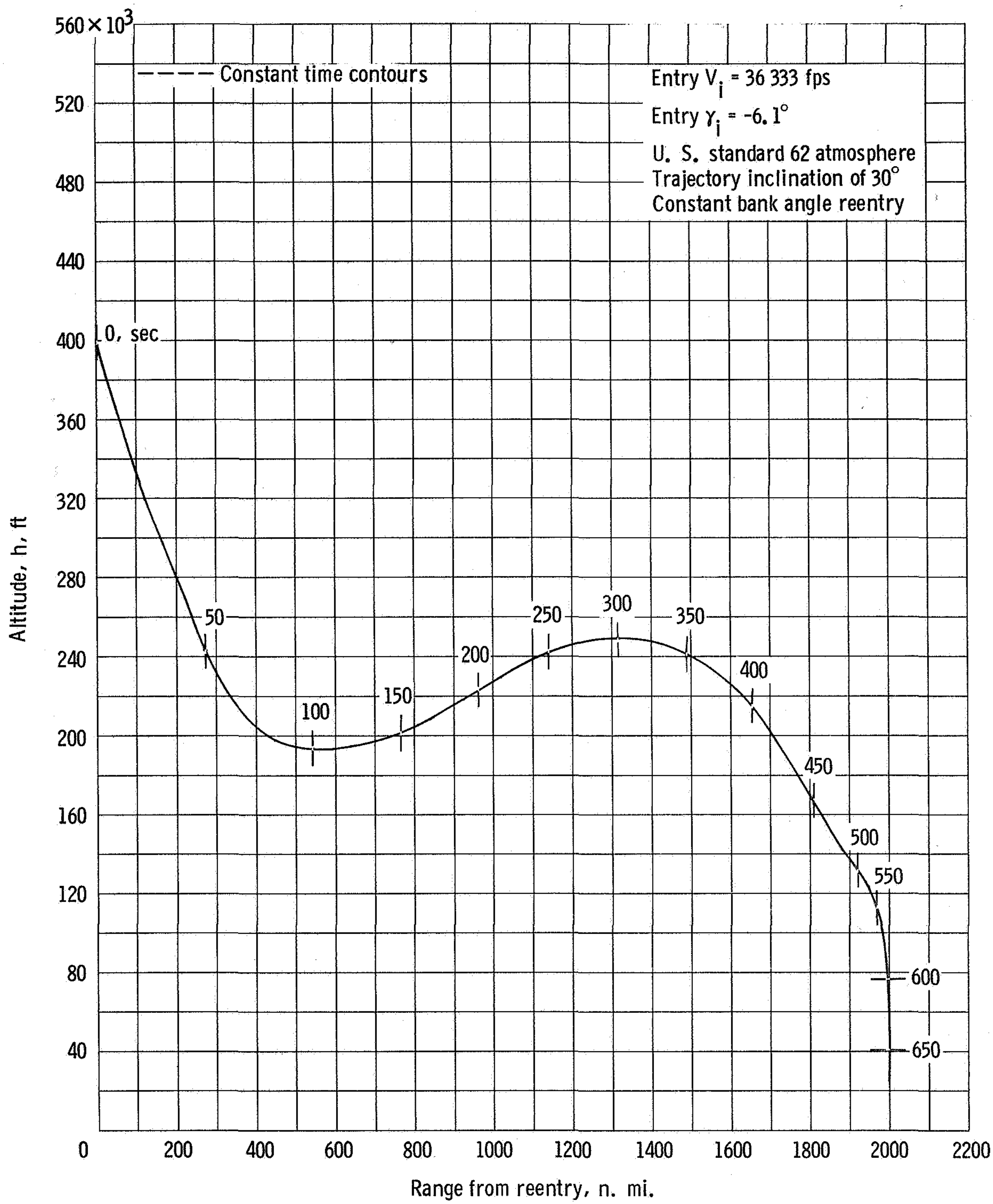

Figure 8. - Altitude-range profile for high-speed guided reentry.

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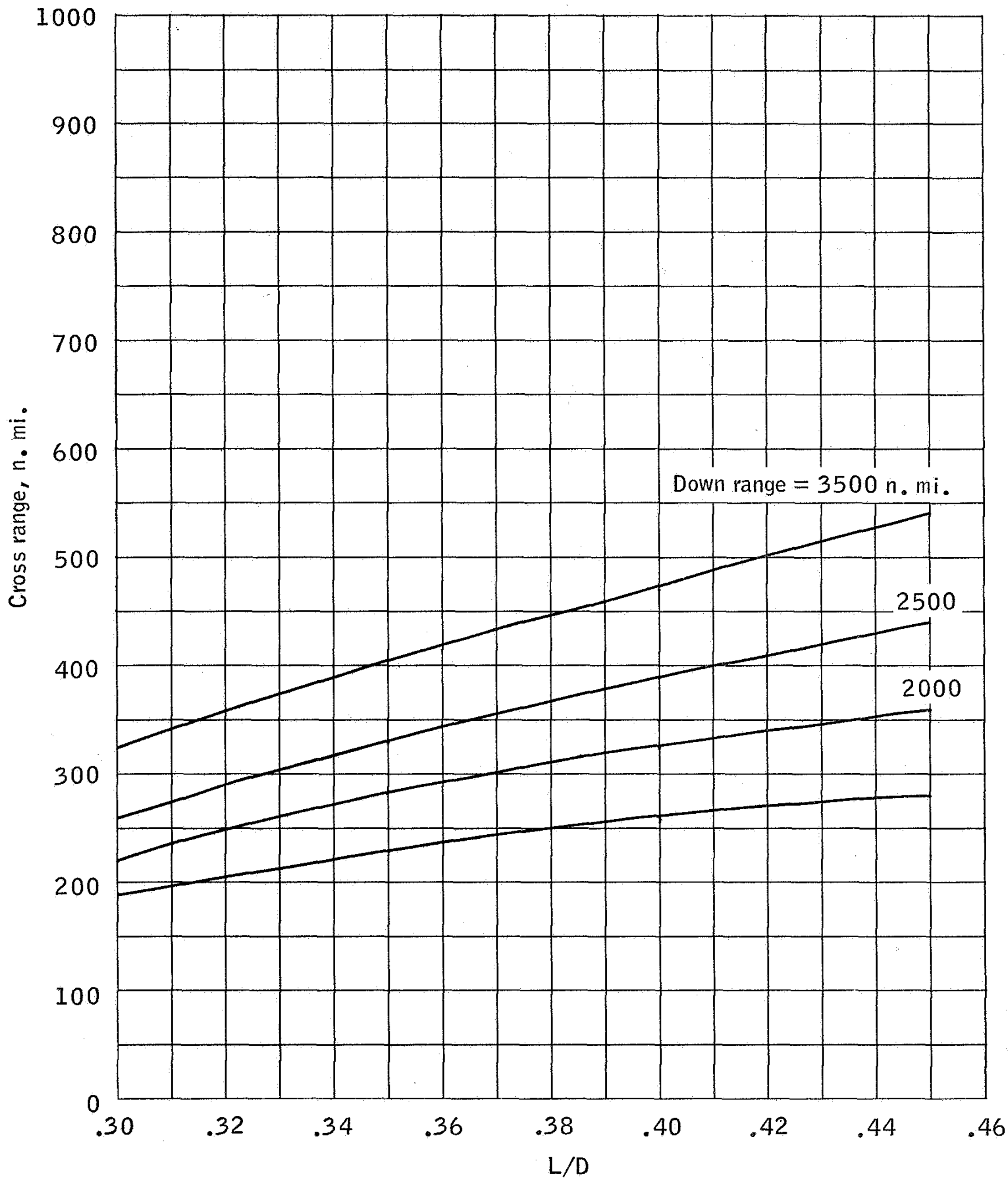

Figure 9.- Cross-range distance versus L/D as a function of down-range distance.

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Plot No. 15,770
Date 7/25/66 Walter Scott

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